FUZZY LOGIC FOR THERMAL PROCESS

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CHEMICAL ENGINEERING
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by

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the requirements for the
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CERTIFICATION OF APPROVAL

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7885

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Approved by,

(Ir. Dr. Halim Shah Maulud)

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TRONOH, PERAK

July 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHD NAIM BIN MOHD ZAINI

ABSTRACT

A Closed loop control system incorporating fuzzy logic has been developed in this project to control the temperature of thermal process. The main purpose of this project is to compare the performance of current proportional-integral-derivative (PID) method that widely used in industry with the Fuzzy Logic Control as an alternative. The proposed fuzzy logic to the thermal process in this research is implemented to the water bath temperature control system to represent the thermal process. Prior to the development of fuzzy logic controller incorporating with a control scheme, several control schemes has been developed in order to select the best control scheme. The best tuning PID formulas that best fit for each control scheme was also taken into consideration to provide the best response of temperature versus time. The temperature controlling was simulated in two problems which are set-point and disturbance change. It was demonstrated in the simulation test of those two problems of thermal process that fuzzy logic is much more capable than the current temperature controller, PID controller based on the result of temperature versus time.

ACKNOWLEDGEMENTS

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First and foremost the author's utmost gratitude goes to the author's current supervisor, Ir. Dr. Abd. Shah Maulud and previous supervisor, Mr. Nasser Mohamad Ramli. Without their guidance and patience, the author would not be succeeded to complete the project. To the Final Year Research Project Coordinator, Dr. Khalik M. Sabil to provide with all the information required to complete the project.

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CHAPTER 1

INTRODUCTION

1.1 Background Study.

A case study on fuzzy logic control for thermal processes has been carried out using simulation method. Modeling of systems is a very essential concept in developing an effective control system in which will reflect the simulation of the physical processes.

While modern control theory has made modest inroad into practice, fuzzy logic control has been rapidly gaining popularity among practicing engineers. This increased popularity can be attributed to the fact that fuzzy logic provides a powerful tool that allows engineers to incorporate human reasoning in the control algorithm. As opposed to the modern control theory, fuzzy logic design is not based on the mathematical of the process. The controller designed using fuzzy logic implements human reasoning that has been programmed into fuzzy logic language (membership function, rules and the rule interpretation).

The process chosen for this project is about the thermal process problem, specifically represented by water bath temperature control system whereby its mathematical model for this system is extracted from *Ashok Kumar Goel and Surekha Bhanot (2005)* In this project, the author concentrate on fuzzy logic control as an alternative control strategy to the current proportional-integral-derivative (PID) method widely used in industry. Prior to that, several process control schemes has been developed with the PID tuning formulas to select only one the best control scheme with its best PID tuning parameter to make it as basis for comparison with fuzzy logic control.

Then, a closed loop system incorporating fuzzy logic has been developed based on selected control scheme.

1.2 Problem Statement.

A various types of thermal processes are applied in industries for example like thermal cracking, thermal reforming, or thermal polymerization and many more. It is well known that thermal processes, regardless technological object in which these take place, possess inherent nonlinearity and time delay phenomena, and often time-varying parameters too especially the temperature. The yield or product of the reaction in the thermal process greatly affected by the operating temperature condition of that process. So, in this case controlling the temperature of the process is very is important as:

- it directly affects the process safety and reliability
- it determines the quality of the products produced by a process
- it can affects on how efficient the process is operated
- it has a major impact on the profitability of a company

To achieve this control, any equipment that is used in the thermal process is generally equipped with a control system in order to provide appropriate heating and cooling functions. The thermal processes is often controlled using a proportional-integral (PI) or proportional-integral-derivative (PID) controller; this is a well-developed control technique widely used in many industries. However, it is also well known that PID controllers exhibit poor performance when applied to system containing unknown nonlinearity such as dead zones saturation and hysteresis. It is further understood that many temperature control processes are nonlinear. Equal increment of heat input, for example, do not necessarily equal increments in temperature rise in many processes, a typical phenomenon of nonlinear systems.

The complexity of these problems and implementing conventional controllers to eliminate variations in PID tuning motivate the author to investigate intelligent control technique such as fuzzy logic as a solution to controlling systems in which time delays, nonlinearities, and manual tuning procedures need to be addressed.

1.3 Objectives of Study

The main objectives of this project are as follow:

- To model and simulate several control scheme to control the temperature of thermal process using SIMULINK in MATLAB
- To get the suitable tuning formula for PI and PID controllers that best fits with each advanced control scheme and provide the desired response of temperature versus time
- To study and analyze the response of each control strategy applied and choose the best response
- To develop a Fuzzy Logic Control scheme based on selected control strategy
- To compare the control responses between FLC with the PID response of the selected control strategy

1.4 Scope of studies

The scope of study for Fuzzy Logic for thermal process project covers:

- Advanced control schemes which are as Feedback Feed, Forward control , Cascade Control , Feed Forward Control, Adaptive Control and Fuzzy Logic Control
- The characteristics, functions , effects and formulas for Proportional Integral (PI), and Proportional Integral Derivatives (PID) controllers
- Selection for best tuning formulas for PI and PID controllers that best fits with each advanced control scheme and give desired result for temperature control
- Analysis on PI and PID controllers performance for response of temperature versus time in term of oscillation, settling time, overshoot and area under the graph
- Designing the Fuzzy Logic Control based on selected control strategy as an alternative control.

CHAPTER 2
LITERITURE REVIEW

2.1 THERMAL PROCESS

According to *(Dale E. Seborg, Thomas F.Edgar, Duncan A (2004)*

> The foundation of process control is process understanding. Thus, what is the definition of a process? Process is the conversion of feed material to products using the chemical and physical operation. In operation, the term process to be used for both the processing operation and processing equipment *(p.2)*

Meanwhile, thermal process is any process that utilizes heat, to accomplish chemical change; for example, thermal cracking, thermal reforming, or thermal polymerization.

2.2 PROCESS MODELING

The Fuzzy Logic proposed in this research is implemented as a controller for simulated water bath system. The system has three input variables which are inlet temperature; ***Ti***, heat input; ***Q*** and flow rate; ***F***. Input variables can be divided into manipulated variable and disturbance variable. In this system, the manipulated variable is ***Q*** and disturbance variables are ***Ti*** and ***F***. The output variable is tank temperature; ***T***. The mathematical model for a water bath system has been developed with the following specifications from *Ashok Kumar Goel and Surekha Bhanot (2005)*: water tank capacity: 12 liters,, inlet water temperature: 25°C, base heater: 2500 watts, flow rate of water: 1 liter/min, and system time delay. The control objective is to regulate the temperature of water in tank. The process of water bath system can be represented by the equation (*a)* below.

$$\frac{dT}{dt} = \frac{F(T_i - T)}{V} + \frac{Q}{V\rho C_p} \qquad (a)$$

Where T is tank temperature, F is flow rate, Ti is inlet temperature, V is volume of the tank, Q is heat input, C_p is specific gravity and ρ is density of the water. The value of volume of the tank, volume of the tank, specific gravity, density of the water is constant.

2.3 PROCESS CONTROL SCHEME

2.3.1 Feedback Control

Feedback control is the basic of closed-loop control system that can be represented by the general block diagram shown in the figure below.

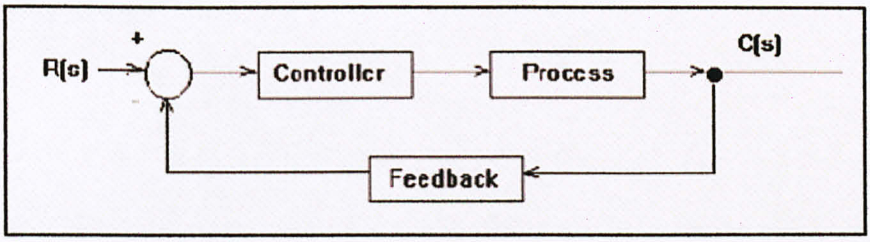


Figure 2.1: The concept of the feedback loop to control the dynamic behavior of the output of the process.

In this configuration a feedback component is applied together with the input R. The difference between the input and feedback signals is applied to the controller. In responding to this difference, the controller acts on the process forcing C to change in the direction that will reduce the difference between the input signal and the feedback component. This, in turn, will reduce the input to the process and result in a smaller change in C. This chain of events continues until a time is reached when C approximately equals R. A closed-loop system is able to regulate itself in the presence of disturbance or variations in its own characteristics

2.3.2 Feed Forward Control

Since control action can only occur if a deviation occurs between the set point and the measured variable, perfect control is not possible. Therefore, feedback control fails to provide predictive control action to compensate for the effects of known disturbances. Feed forward control was developed to counter some of these limitations. Its basic premise is to measure the important disturbance variables and then take corrective compensatory action based on a process model. The basic concept is to measure important disturbance variables and take corrective action before they upset the processes. Feed forward control theoretically can become a perfect control and it will not affect the stability of the system.

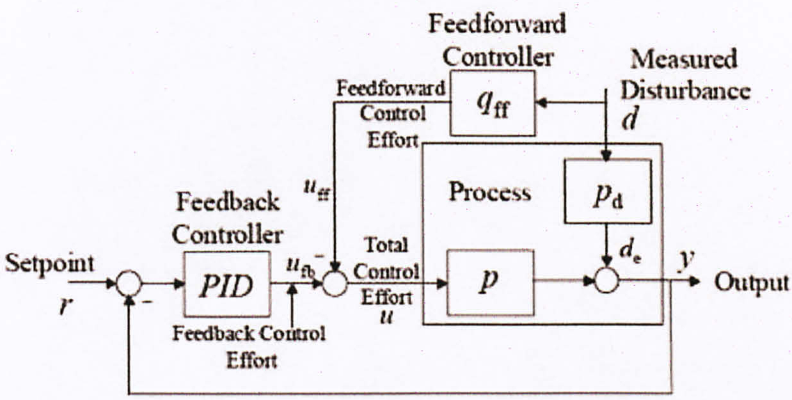


Figure 2.2: Traditional Feedforward/feedback control structure

2.3.2 Cascade Control

Cascade control is also widely used in the chemical process industries and especially in cases where there may be nonlinear behavior in the dynamics of the control loop. It also addresses the main drawback of conventional feedback control namely the fact that control action only occurs where the controlled variable deviates from the set point. Cascade control implementation is a familiar task because the architecture is comprised of two ordinary controllers from the PID family. Cascade is specifically designed for improved disturbance rejection. In a traditional feedback loop, a controller adjusts a manipulated variable so the measured process variable remains at set point. The cascade design requires that you identify a secondary process variable (call the main process variable associated with original control objective the primary variable). This secondary process variable must meet certain criteria:

- It must be measurable with a sensor
- The same valve used to manipulate the primary variable manipulate the secondary variable
- The same disturbances that disrupt the primary variable must also disrupt the secondary variable
- The secondary variable must be inside the primary process variable, which means it responds well before the primary variable to disturbances and final control element manipulations

A cascade requires two sensors and two controllers but only one final control element because the output of the primary controller, rather than going to a valve, becomes the set point of the secondary controller. With this nested architecture, success in a cascade implementation requires that the settling time of the(inner) secondary loop is significantly faster than the settling time of the primary (outer) loop.

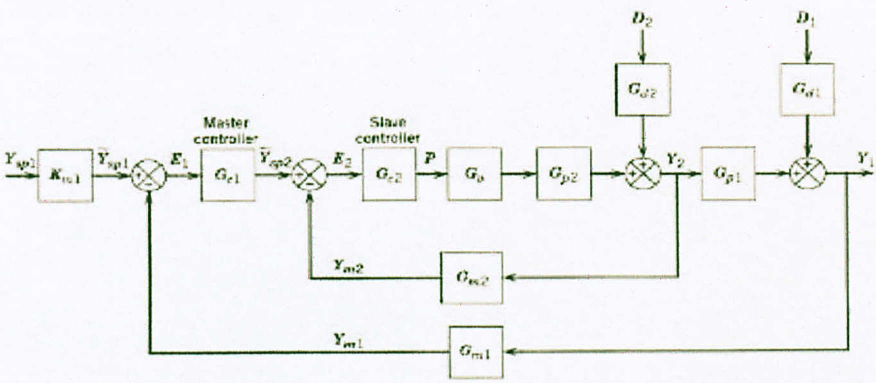


Figure 2.3: Block diagram of the cascade control system

2.3.4 Adaptive Control

An adaptive control is one in which the controller parameters are adjusted automatically to compensate for changing process conditions. Examples of changing process conditions that may require controller retuning are:

- changes in equipment characteristics – heat exchanger fouling, catalyst deactivation
- Unusual operational status – start up, shutdown, failures
- Inherent nonlinear behavior
- Changes in product specifications or product flow rates

When the process changes can be anticipated or measured directly, and the process is reasonably well understood, the gain scheduling approach (programmed adaptation) can be employed. The adaptive controller is also known as self tuning controller where the parameters in the process model are updated as new data are acquired (using on line estimation methods), and the control calculations are based on updated model. Three set computations are employed in adaptive controls which are estimation of the model parameters, calculation of the controller settings and implementation of the controller output in a feedback loop.

2.4 FUZZY LOGIC CONTROLLER COMPONENTS

Fuzzy Logic was initiated in 1965 by Lotfi A. Zadeh, professor for computer science at the University of California in Berkeley. Basically, Fuzzy Logic (FL) is a multi-valued logic, which allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low, and so on. Notions like rather tall or very fast can be formulated mathematically and processed by computers, in order to apply a more human–like way of thinking in the programming of computers.

Fuzzy logic control methods represent a rather new approach to the problem of controlling complex non-linear system, the system in which mathematical model is difficult or impossible to describe, and also the systems with multiple inputs and outputs characterized by hardly defined internal interference. There are numerous examples of applications of fuzzy logic on the technical and nontechnical systems, especially complex systems in the industry, economy, medicine and more.

In this section, the author presents the main ideas underlying the FLC. **Figure 2.4** below shows the basic configuration of an FLC, which comprises four principal components: a *fuzzification interface, a knowledge base, decision making logic,* and a *defuzzification interface*

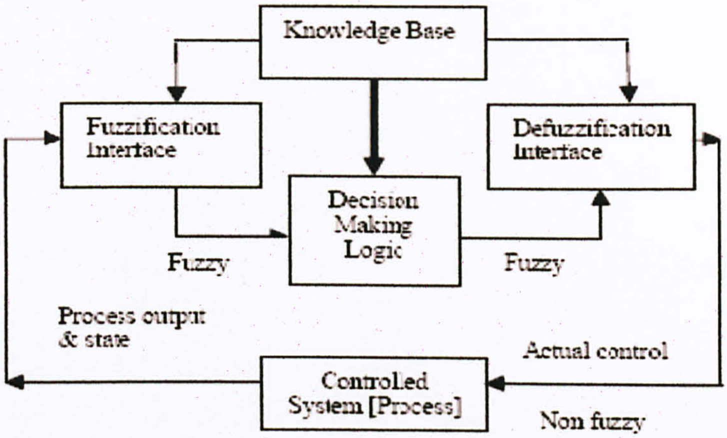


Figure 2.4: Fuzzy Logic Controller

CHAPTER 3
METHODOLOGY /PROJECT WORK

3.1 PROCEDURE/ METHOD

For this research project, a sequence of methodology has been developed in order to assist in conducting the project and ensuring the best result as a return. These are the methodology of the research project.

3.1.1 Research.

The project is started with the research on background of study and the main objectives of the project in order to get overall overview about the project. This have been done by consulting the supervisor in this project and read several the related journals to this project. The research also covered the scope of study, the problem definition and the literature review or the basic theory in fuzzy logic. In addition, the author does a research on the controller tuning formulas for PI and PID controllers. The main sources are the internet and the Universiti Teknologi PETRONAS Information Recourse Center (UTPIRC).

3.1.2 Develop the Process Control Schemes in SIMULINK

Before developing of fuzzy logic modeling, it's crucial to find the appropriate control strategy and also the best tuning for which it will be used as a basis of comparison for the fuzzy logic model responses.

Some of control strategies which will be considered and studied in this project are listed as below:

- Feedback Control strategy.
- Feed forward Control strategy.
- Adaptive Control strategy.
- Cascade Control strategy.

These control schemes are developed by using the SIMULINK in MATLAB. SIMULINK is a software package for modeling, simulating, and analyzing dynamic systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. The process control schemes are constructed in the SIMULINK by arranging and link the different types of blocks. Each of the block diagram models which representing the above control strategies were developed to tackle two different kinds of control problems, namely Servomechanism problem (Set-point changes) and Regulatory problem (Disturbance Changes). Then, the tuning parameters for the controllers (which are PI and PID Controller) were constructed by using command line function provided by MATLAB M-files.

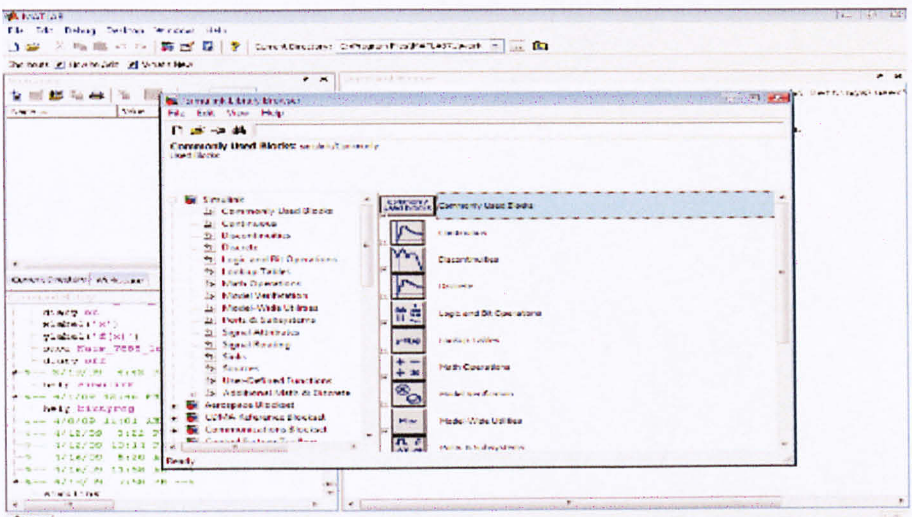


Figure 3.1: SIMULINK library browser in MATLAB

3.1.3 Controller Tuning Formulas

The controllers tuning formulas are classified base on the control problem either servomechanism problem or regulator problem and type of controllers either PI or PID. In this project, the tuning formulas are divided into four groups which are PI controller for servomechanism problem, PI controller regulator problem, PID servomechanism problem and PID controller regulator problem. Any tuning formulas that comply with the process model will be categorized within these four groups. Each control scheme in SIMULINK is evaluated by using PI and PID controllers and the temperature response versus time then is analyzed. The purpose of controller tuning is to determine the tuning formula for that best suit with PI and PID controllers in every control scheme for servomechanism problem and regulator problem that can give desired result for temperature control. The tuning process is done by using the SIMULINK and M-File.

The M-File is a blank template where the user can enter related coding to and enable to call the result from SIMULINK. By using M-File, the author has defined the value for Kc, Ti, Td & di, enter the equation for the controllers tuning formulas and enter the coding for plotting the graph. The M-File will display all the graphs for the tuning formulas base on the setting of the control schemes in SIMULINK. Below is the example of coding that is used in M-File

```
%For Setpoint
%Step
K1=12.63;T1=5.95;d1=5;

%IAE
Kc=(0.758/K1)*((d1/T1)^-0.861);Ti=T1/(1.02-
0.323*(d1/T1));Td=0;
sim('thermal_process_feedback');
figure(1);
plot(time,T);
title('Close Loop IAE Response-Setpoint');
xlabel('Time(s)');
ylabel('Temperature Response (deg C)');
grid on;


%ITAE
Kc=(0.586/K1)*((d1/T1)^0.916);Ti=T1/(1.03-0.165*(d1/T1));Td=0;
sim('thermal_process_feedback');
figure(2);
```

```
plot(time,T);
title('Close Loop ITAE Response-Setpoint');
xlabel('Time(s)');
ylabel('Temperature Response (deg C)');
grid on;
```

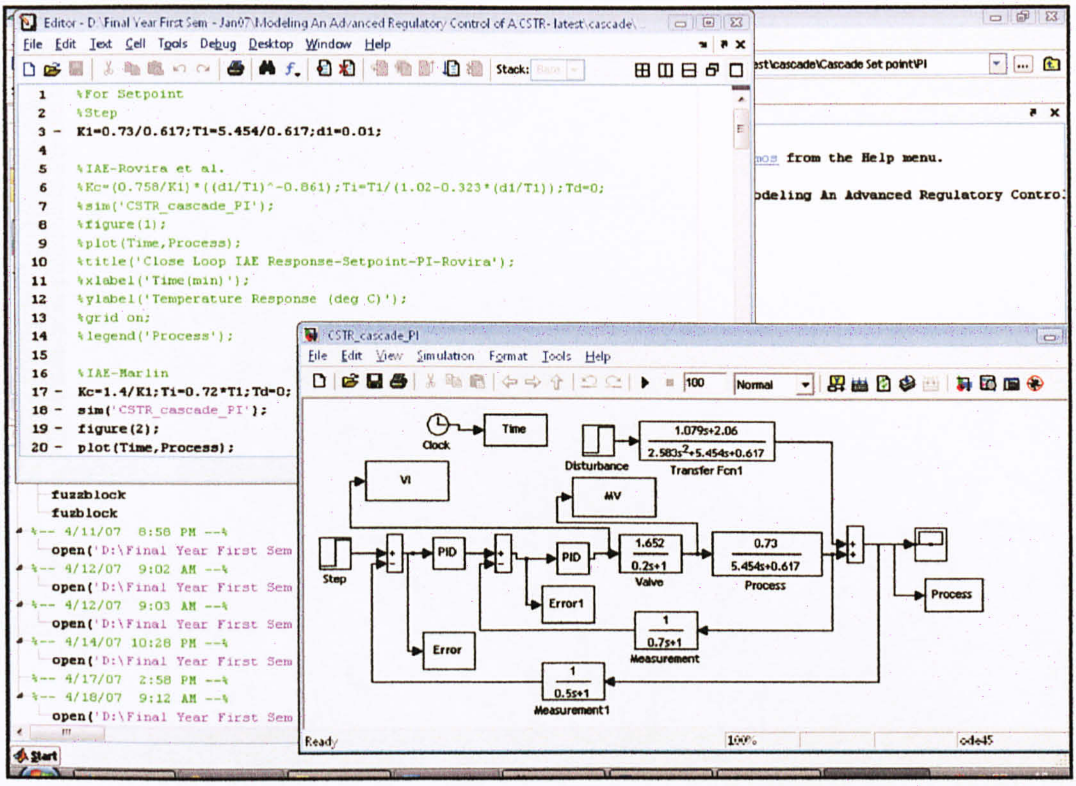


Figure 3.2: The relationship between M-File and SIMULINK

3.1.3 Selection for the Best Controller Tuning Formula

The controller tuning is implemented on each control schemes using PI and PID controllers for servomechanism problem and regulator problem. Different tuning formulas for PI and PID will give different results of temperature response versus time and only the best results that fulfill the criteria are selected. In evaluating the graph for temperature response, four criteria are taken into accounts which are value of overshoot, number of oscillations, settling time and the area under the graph. The desired graph of temperature versus time must have no or less value of overshoot, no or less oscillation , faster settling time and lower value of area under the graph.

Time and Error are the values that have been calculated through combination of SIMULINK and M-File and displayed in the Workspace.

The area under graph for each graph is calculated by using Trapezium Method with the coding below:

```
x = Time;
>> y = Error;
>> Area = trapz(x,y)
Area =
  10.7775
```

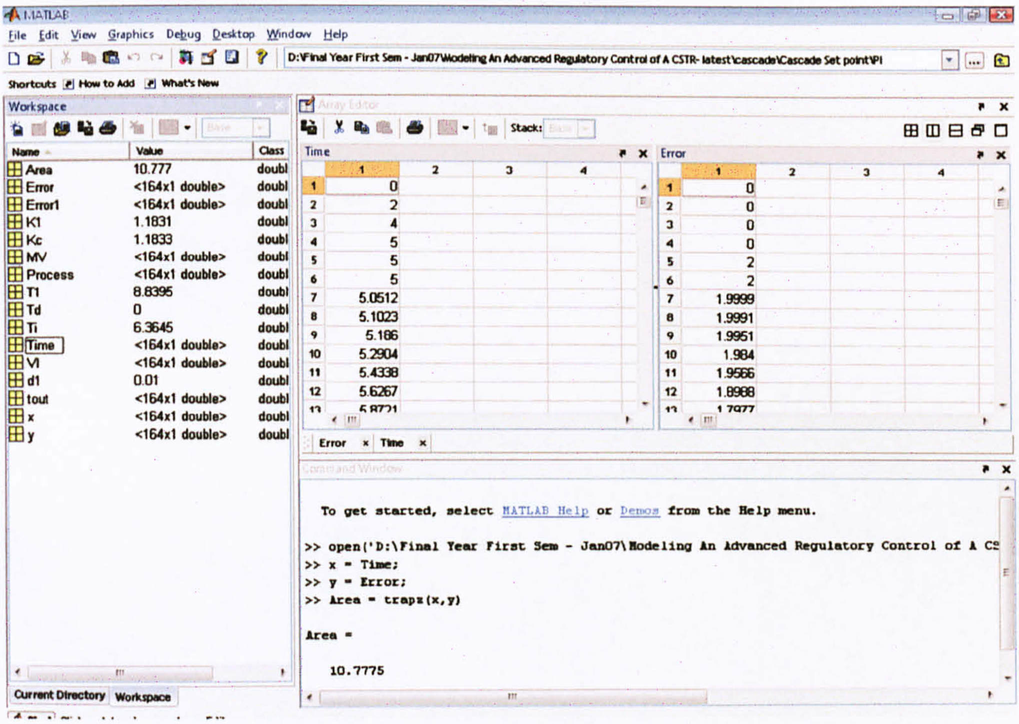


Figure 3.3: Calculation for area under the graph using Trapezium Method base on the value of variable “Time” and variable “Error” from Workspace

Besides area under, in this project, settling time of each response is recorded to determine the best control response. **Settling time** can be defined as the time required for an output to reach and remain within a given error band, usually symmetrical about the final value following some input stimulus.

The figure below shows the on how the settling time is determined from a control output response:

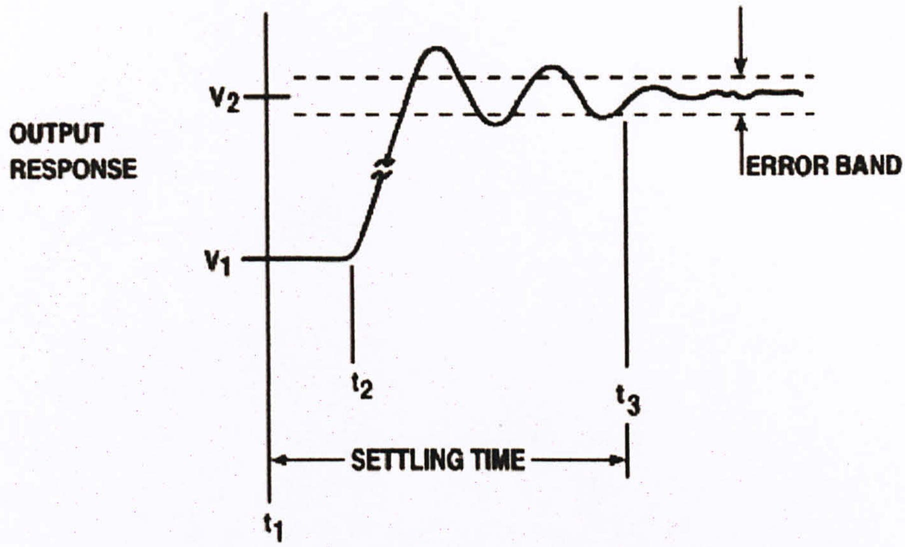


Figure 3.4: Example of settling time of an output response

3.1.4 The Development Of Fuzzy Logic Controller (FLC)

Fuzzy Logic is one of the advanced process control scheme and it can be used as the alternative approach to control the thermal process problem by using the Fuzzy Logic Controller (FLC). In this project, the development of fuzzy modeling will be based on Fuzzy Logic Toolbox which is the collection of functions built on the MATLAB numeric computing environment. It provides tools to create and edit fuzzy inference systems within the framework of MATLAB. Furthermore, in MATLAB is also possible to integrate the fuzzy systems into simulations with Simulink, or can even build stand-alone C programs that call on fuzzy systems which are built with MATLAB. This toolbox relies heavily on graphical user interface (GUI) tools to help the user to accomplish the modeling work, although the user can work entirely from the command line if the user prefers [14].

The toolbox provides three categories of tools [14]:

- Command line functions:

  The first category of tools is made up of functions that user can call from the command line or from user own applications. Many of these functions are

MATLAB M-files, series of MATLAB statements that implement specialized fuzzy logic algorithms. User can view the MATLAB code for these functions using the statement. Also, the user can change the way any toolbox function works by copying and renaming the M-file, then modifying the user's copy. Furthermore, user can also extend the toolbox by adding user's own M-files.

- Graphical, interactive tools:
  Secondly, the toolbox provides a number of interactive tools that let the user to access many of the functions through a GUI. Together, the GUI- based tools provide an environment for fuzzy inference system design, analysis, and implementation.

- Simulink blocks and examples:
  The third category of tools is a set of blocks for use with the Simulink simulation software. These are specifically designed for high speed fuzzy logic inference in the Simulink environment.

The software package is consisted of the following module: FIS (Fuzzy Inference System) editor; Membership Function editor; Rule Editor; Fuzzy Controller with Rule Viewer. The FIS Editor (**Figure 3.5**) makes the heart of the designed fuzzy controller. With the help of Rule editor and the Membership Function Editor, the FIS editor completely defines a controller ready for action.

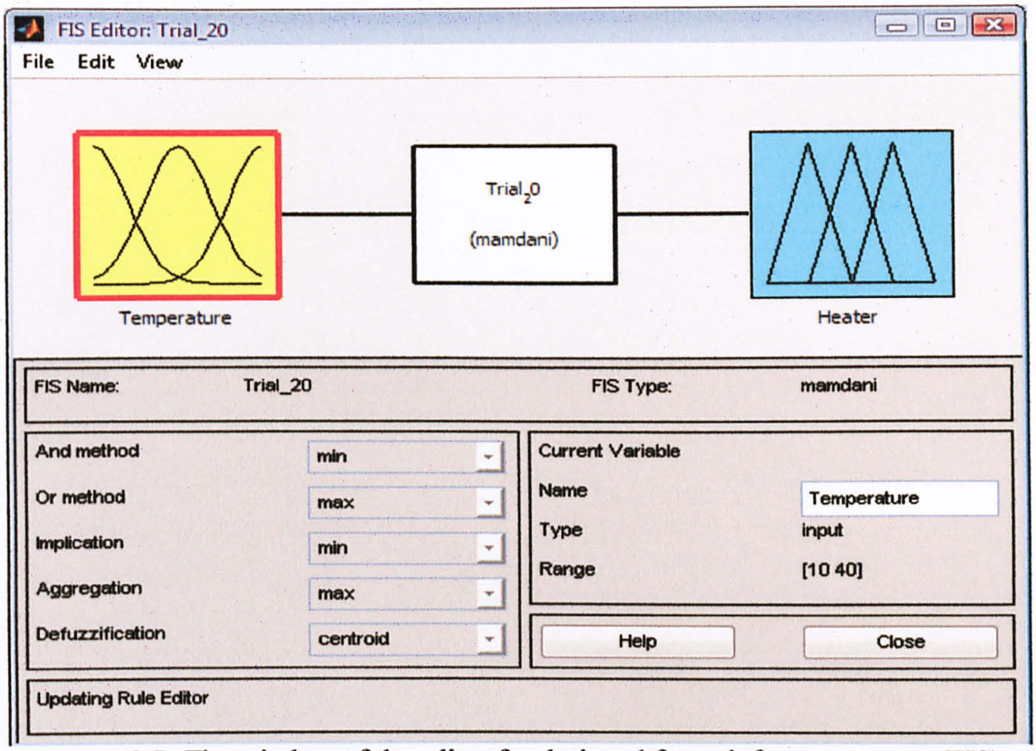


Figure 3.5: The window of the editor for designed fuzzy inference system (FIS)

In this project, Fuzzy Logic Control (FLC) was developed by using Mamdani Fuzzy inference method. The FLC was designed individually as such to perform for servomechanism problem (set-point changes) and regulatory problem (disturbance changes) respectively.

In the development of FLC, the input and output variables must first be defined by using the FIS Editor. For this project, the input is the **temperature of the fluid inside the thermal** tank and the **output is the heating duties** required via the heating element.

The process transfer function is used to relate between the amount **heating duties required** to the **temperature of the fluid inside** the thermal water tank. For the input and the output of FLC, each of them has their own membership function. The value of this function determines the element that belongs to the fuzzy set.

There are many types of membership function; triangular and trapezoidal are considered in the development of FLC. For the **input membership function,**

triangular was used while for the **output membership function** the combination of **trapezoidal-triangular was used.** Each of the input and output consists of numbers of membership function. Membership function was designed by using the Membership Function Editor for which each membership can be assigned with different types and values. Moreover, the range of the input and the output is very important in order to define the type and value of the membership functions .

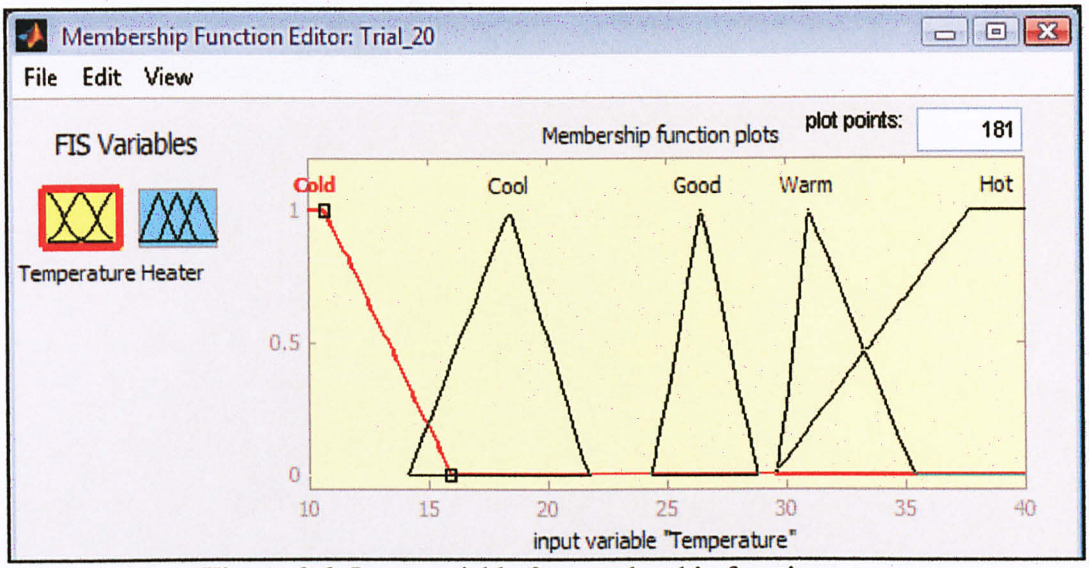


Figure 3.6: Input variable for membership functions

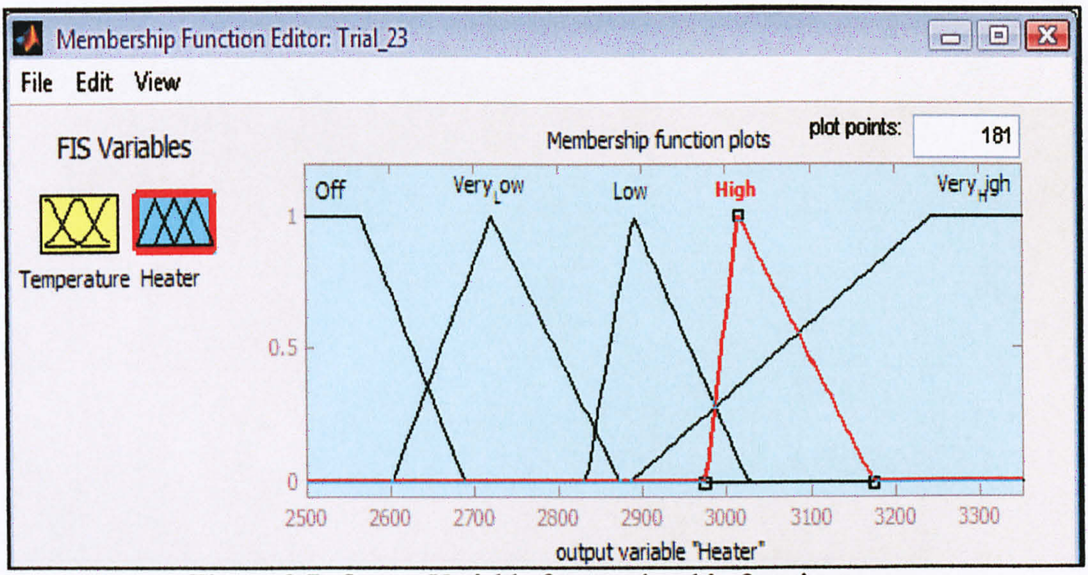


Figure 3.7: Output Variable for membership functions

Each of the membership functions for the input and the output variable are connected by using the Rule Editor. The FLC will give the control response based on the input and the output which are connected by using these rules. Furthermore, the Fuzzy Inference System enables the view of the Rule Viewer and Surface Viewer in which will provide assistance for the further improvement of the FLC design .

List of Rules for Step input: Set-point and Disturbance Changes:

1. If (Temperature is Cold) then (Heater is Very High) (1)
2. If (Temperature is Cool) then (Heater is High) (1)
3. If (Temperature is Warm) then (Heater is Low) (1)
4. If (Temperature is Good) then (Heater is Off) (1)
5. If (Temperature is Hot) then (Heater is Off) (1)

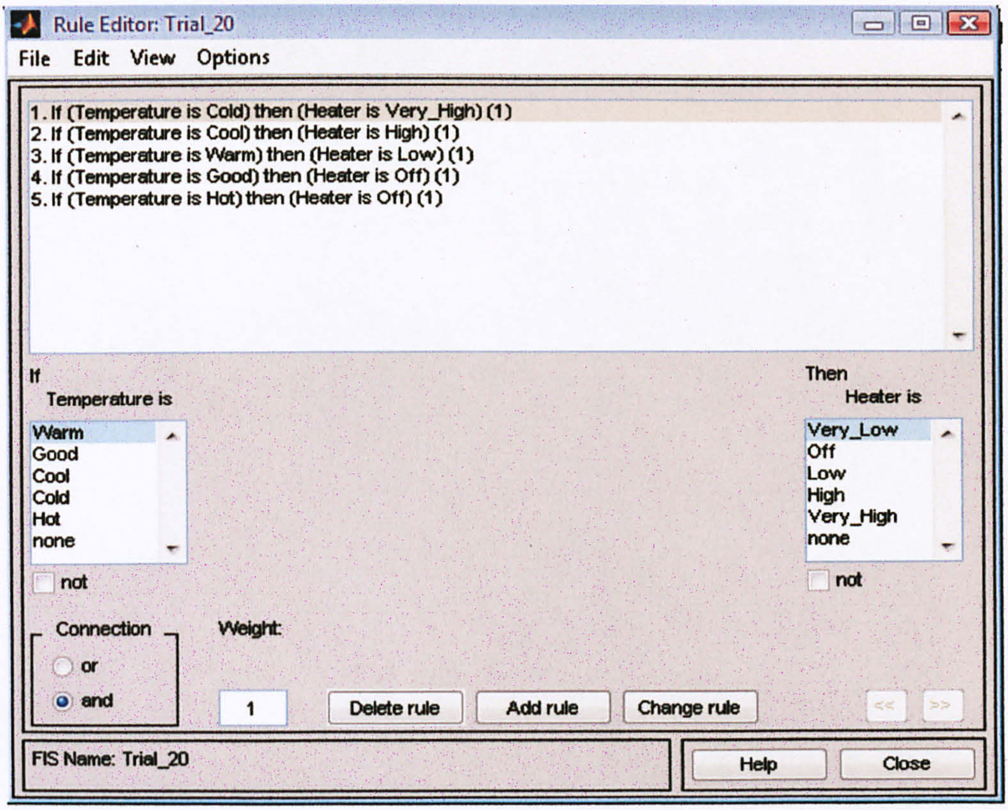


Figure 3.8: The window of Rule Editor for editing the list of rules that defines the behavior of the system

3.2 PROCESS FLOWCHART OF THE PROJECT

The overall methodology of this project can be summarized in the process flowchart as the following:

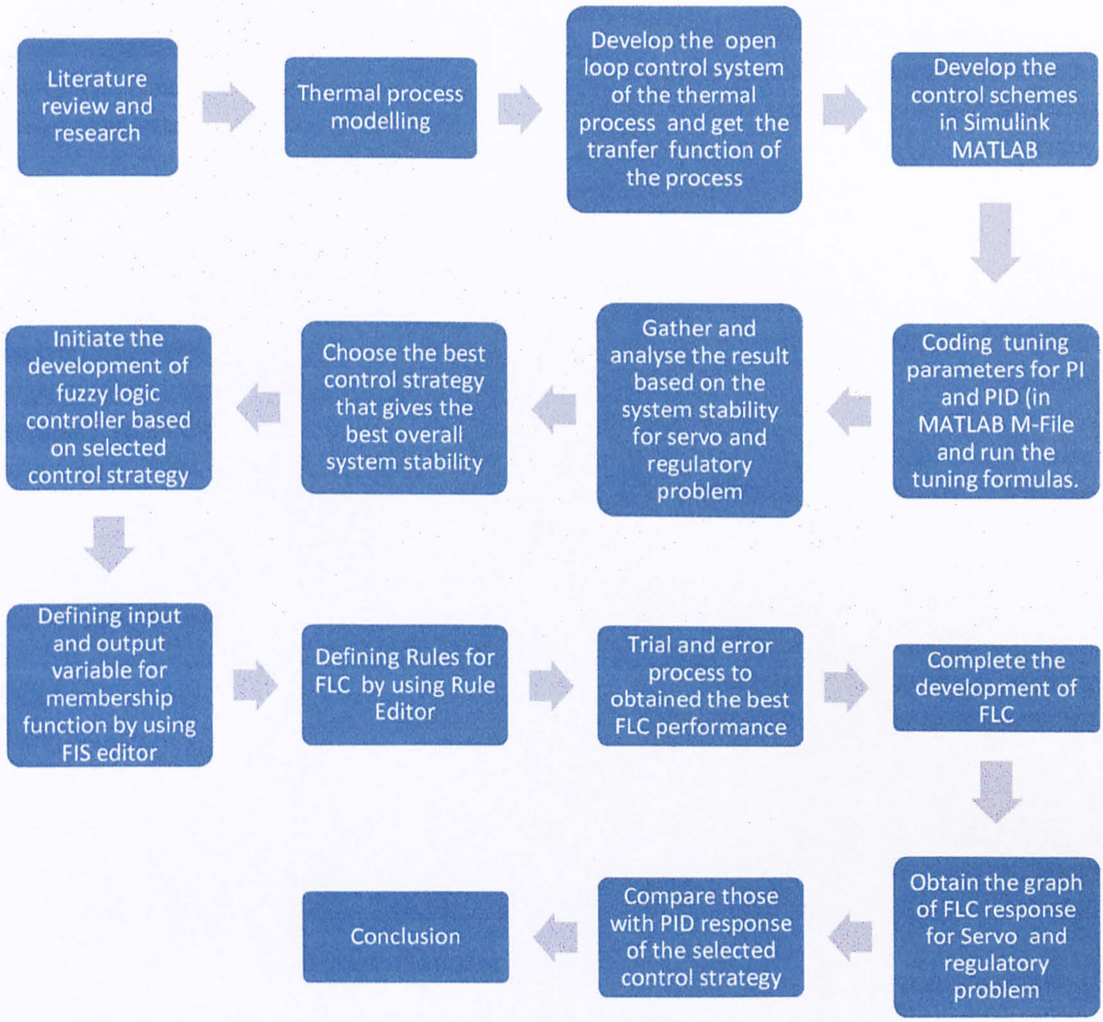


Figure 3.9: Process flowchart of Fuzzy Logic for Thermal process project

3.3 PROJECT TOOL

In this project, the only tool is MATLAB that being used to construct the Fuzzy Logic controller (FLC) and other control schemes.

CHAPTER 4
RESULT AND DISCUSSION

4.1 RESULTS AND DATA ANALYSIS

4.1.1 Open Loop Control System

In this project, the control strategy for thermal process is represented by simulation of water bath temperature control system in SIMULINK in MATLAB. Here is the open loop control system for thermal system of water bath temperature control system.

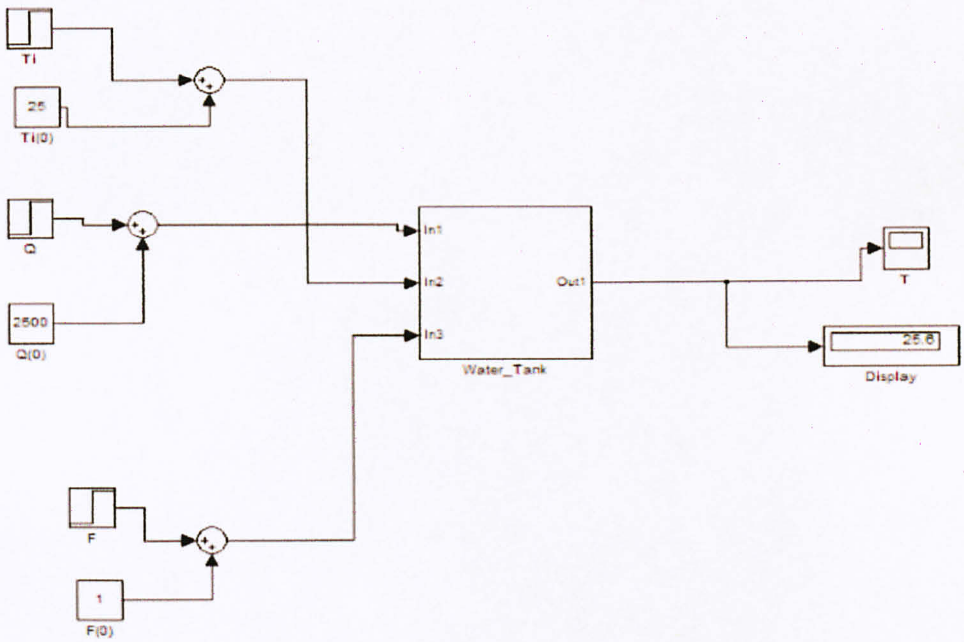


Figure 4.1: Block diagram of Water Bath Temperature Control System

Above figure shows that thermal system has three input variable which are *Ti, Q and* F and one output variable which is *T*. Inside the water tank block diagram in **Figure 4.7** there is another subsystem that relate equation model of the system with the input and output variables.

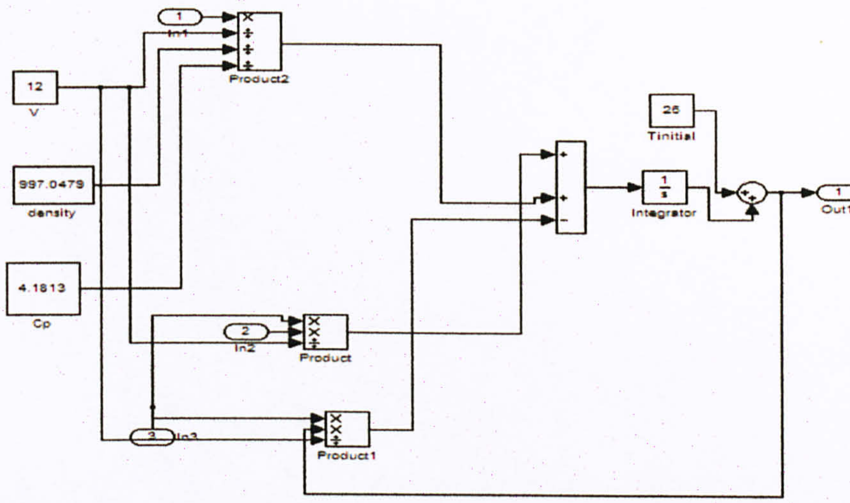


Figure 4.2: Sub-system of Water Bath Temperature Control System

Above figure shows the sub-system of the Water Bath Temperature Control System. In this subsystem, there are three constants which are volume; *V*, density; ρ and heat capacity; Cp.

The Water bath temperature control system used in this study is a First Order plus Dead Time (FOPDT) plant. This is because the simulation result of open loop step response shows the characteristic of FOPDT response. Below is the response:-

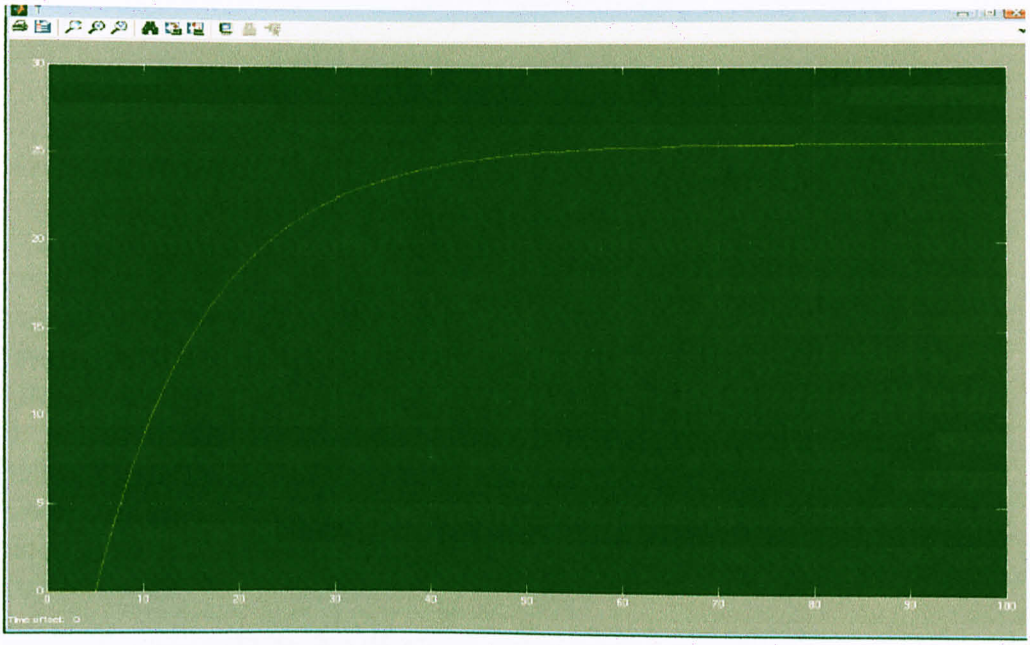


Figure 4.3: Open loop Response of step input.

Above graph is dynamic response of systems in terms of first order plus time delay transfer functions. Generally, Transfer functions of first order process with time delay is given by equation *(b)* below.

$$G(s) = \frac{k}{\tau s + 1} e^{-\theta s} \qquad (b)$$

Where k is process gain, τ is the time constant and θ is time delay. This transfer functions can be determined from graph of Response of step input. From the graph, it is shown that the process is having time delay in the beginning. Then, the plot shows that a first order process does not respond instantaneously to a sudden change in its input. In fact, after a time interval equal to the process time constant (t $= \tau$), the process response is still only 63.2%. From the graph, the author able to find out of the transfer functions of the process which are:

(i) The transfer function relating T to Q is

$$G(s) = \frac{0.01024}{12s + 1} e^{-5s}$$

(ii) The transfer function relating T to Ti is

$$G(s) = \frac{1.024}{12s + 1} e^{-5s}$$

(iii) The transfer function relating T to F is

$$G(s) = \frac{25.6}{12s+1} e^{-5s}$$

4.1.2 Selection for the Best Control Scheme and Controller Tuning

The stability response result obtained for every control strategies will be presented in graphical form. Only those graphs which producing stable responses will be taken into consideration and presented.

In this section, only the graphs producing overall stability according to the type of control scheme that their represented will be presented. The complete results of system stability based on each control schemes studied are presented in the Appendix section of this report.

Some of the general criteria of selection for the system stability are as the following:

- Producing stable responses.
- Not much oscillation.
- The settling time is less.

Generally, the selection criteria will be much according to the following **figure 4.4.**

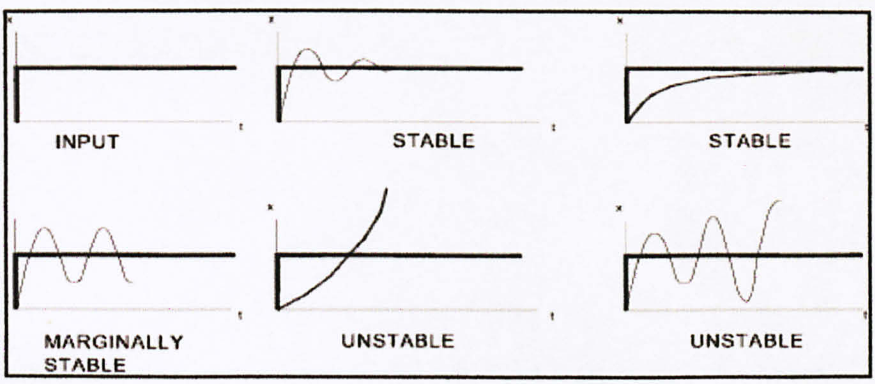


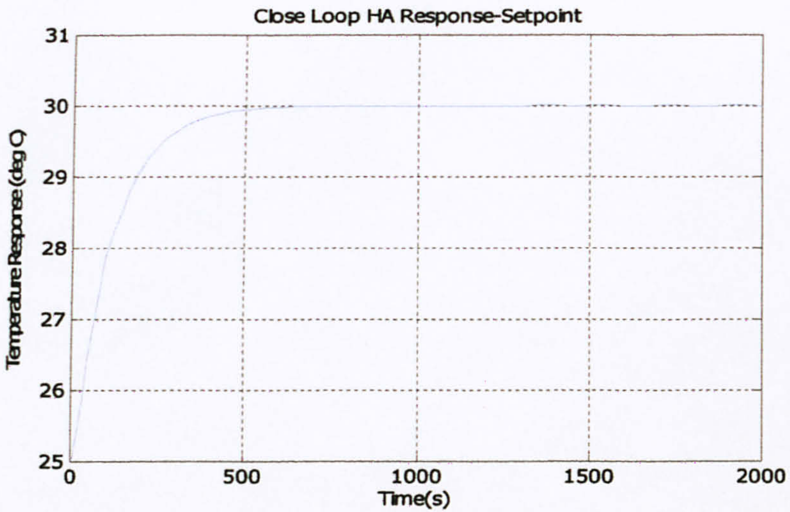
Figure 4.4: Typical types of stability responses resulting from an input.

There are a number of tuning formulas for PI and PID controllers in each control scheme for each control problem that have been evaluated using SIMULINK and M-

File. After the analyzing process, only one tuning formula either PI or PID in each control scheme for both control problems that give best control performance of temperature of water in the tank is chosen.

The trend shown here are the best responses obtained:-.

<table>
<tr><th colspan="2">Feedback</th></tr>
<tr><th>Set point</th><th>Disturbance</th></tr>
<tr><td>



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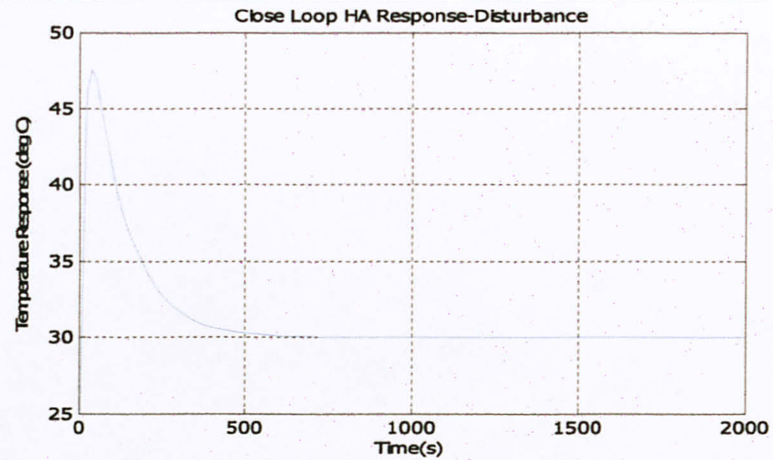
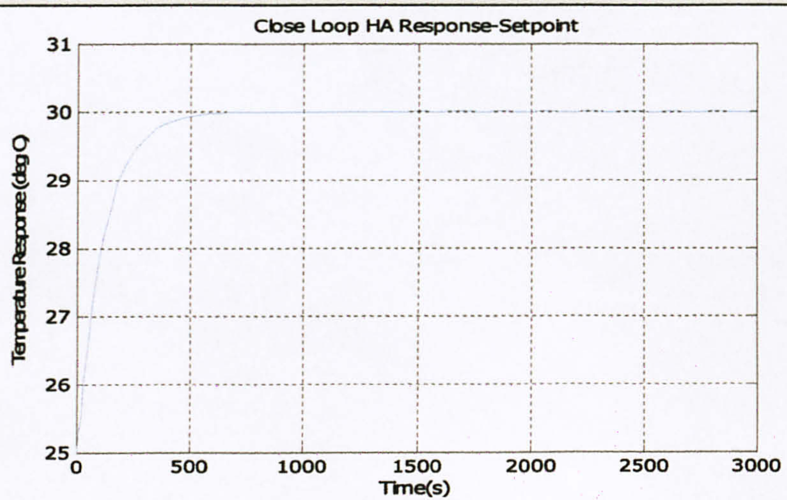
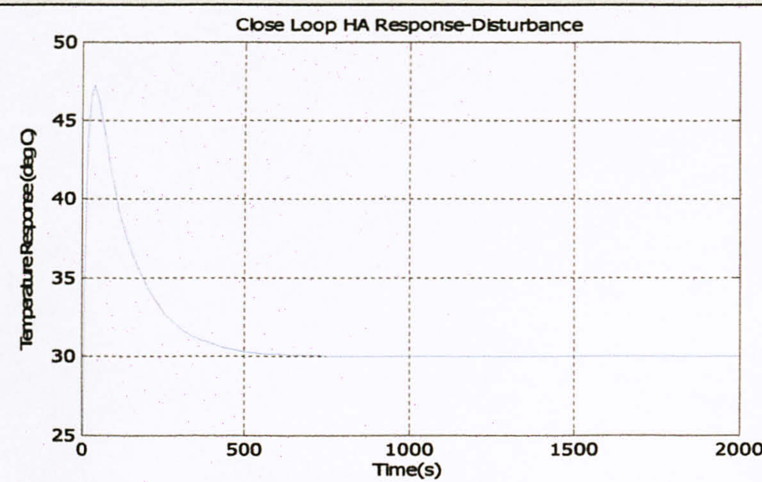


</td></tr>
<tr><th colspan="2">Feed forward</th></tr>
<tr><td>



</td><td>



</td></tr>
</table>

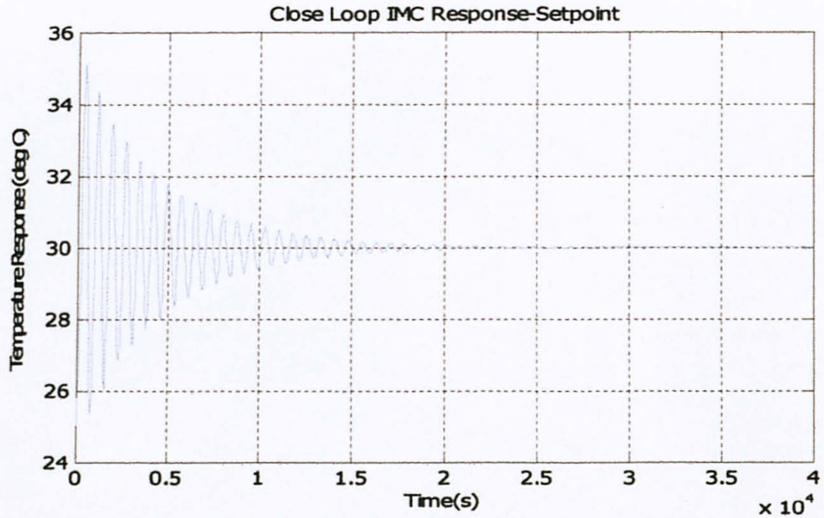
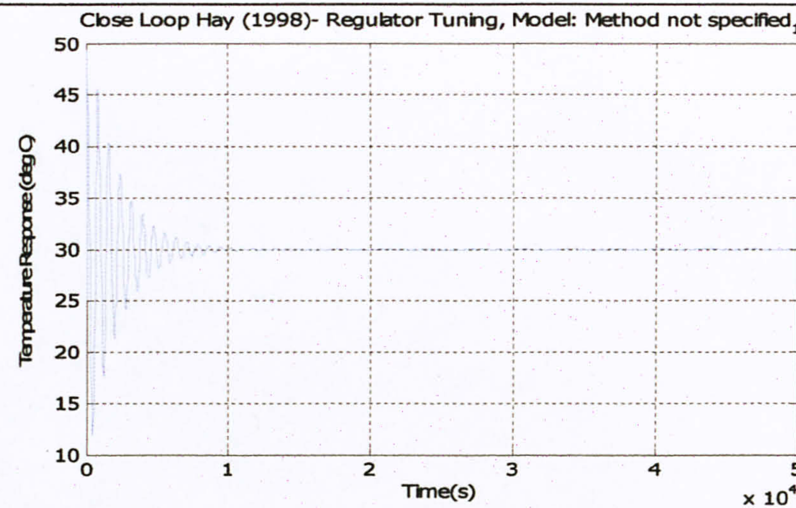
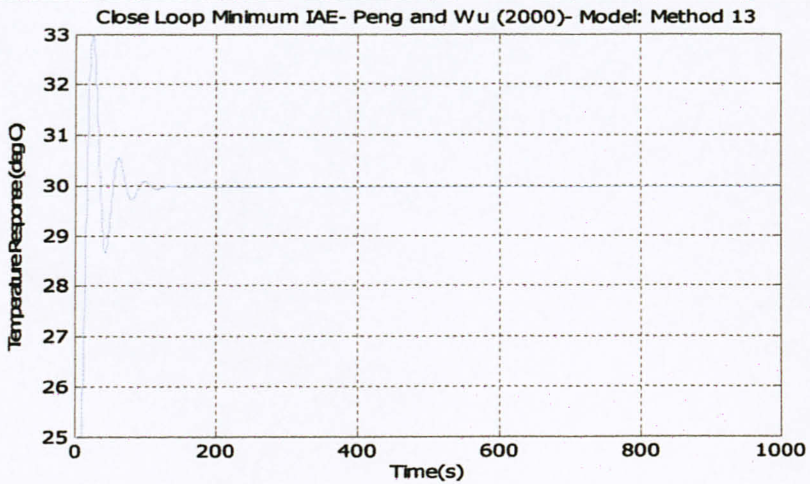
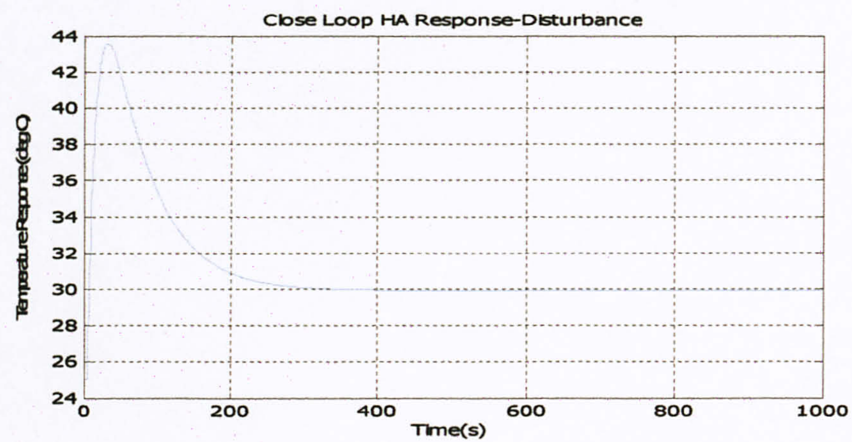
<table>
<tr><th colspan="2">Cascade</th></tr>
<tr><th>Set point</th><th>Disturbance</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><th colspan="2">Adaptive</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

Table 4.1: The best response of temperature versus time for set point and disturbance change for each control schemes

Characteristic	Feedback		Feed forward		Cascade		Adaptive	
	Set Point	Disturbance	Set Point	Disturbance	Set Point	Disturbance	Set Point	Disturbance
Settling Time (s)	620	600	600	628	23000	12000	130	320
Area under graph (error)	504.0216	2587.0000	1007.000	2474.3000	3652.8000	1864.0000	19.5511	81.0388
Tuning Method	PID - HA	PID - HA	PID - HA	PID - HA	PID-IMC	PID- Hay (1998)	PID-Minimum IAE- Peng and Wu (2000)	PID- HA

Table 4.2: Settling time, area under graph and Tuning method that best fit each control scheme

An analysis has been done on all of the graphs of temperature response versus time by considering three criteria. The three main criteria are the number of oscillations, value of overshooting and the settling time (time taken by the system to achieve the new set point or to return to its desired operating point).

By using the three criteria, one graph for each control schemes for servomechanism and regulator response is selected. The type of controller and the tuning formulas for those graphs are recorded. Then, the best control scheme that gives the best graphs of temperature response versus time for servomechanism and regulator problem is chosen.

Based on **Table 4.2**, the result of settling time of adaptive control scheme is the shortest time followed by feedback, feed forward and cascade control scheme. The best tuning rule for servomechanism problem is Minimum IAE- Peng and Wu (2000) (PID) with Adaptive control. For regulator problem, the best tuning rule is HA (PID) with Adaptive control. Adaptive control also shows the less value of area under graph.

Thus, adaptive control is chosen as the best control strategy that will be used in the next to develop fuzzy logic controller. The design of Adaptive Control scheme block diagram (due to step input) which is used as the basis of comparison with the Fuzzy Logic Control is presented as in the following diagram:

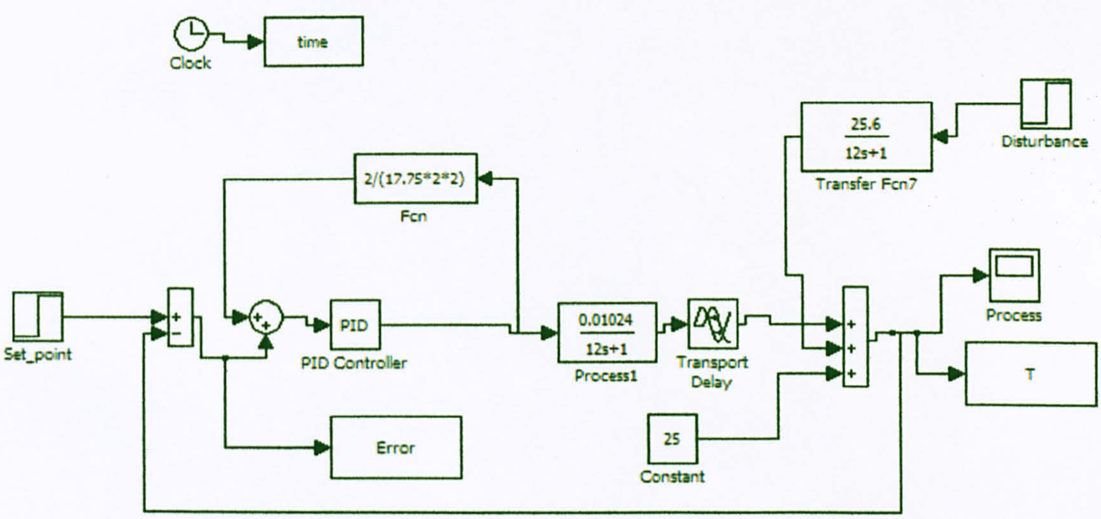


Figure 4.5: Block diagram of Adaptive control scheme

4.1.3 Adaptive Control (PID) versus Fuzzy Logic Control

The Adaptive control scheme then is compared with the Fuzzy Logic Controller (FLC). The Adaptive Control Scheme block diagrams with the Fuzzy Logic Control used to analyze the response and performance of FLC are presented as in the following figures:

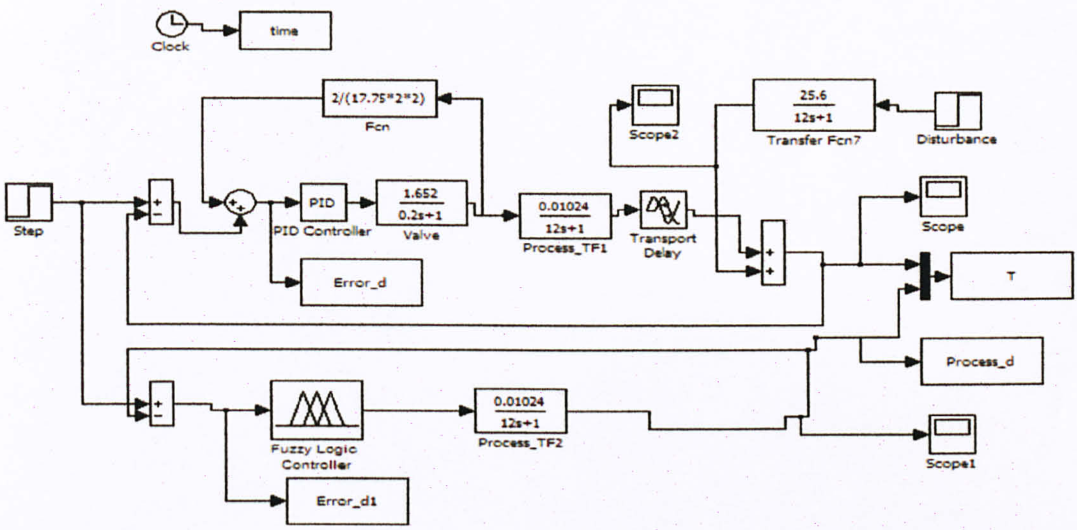


Figure 4.6: Adaptive Control Scheme block diagrams with the Fuzzy Logic Control (Set-point change).

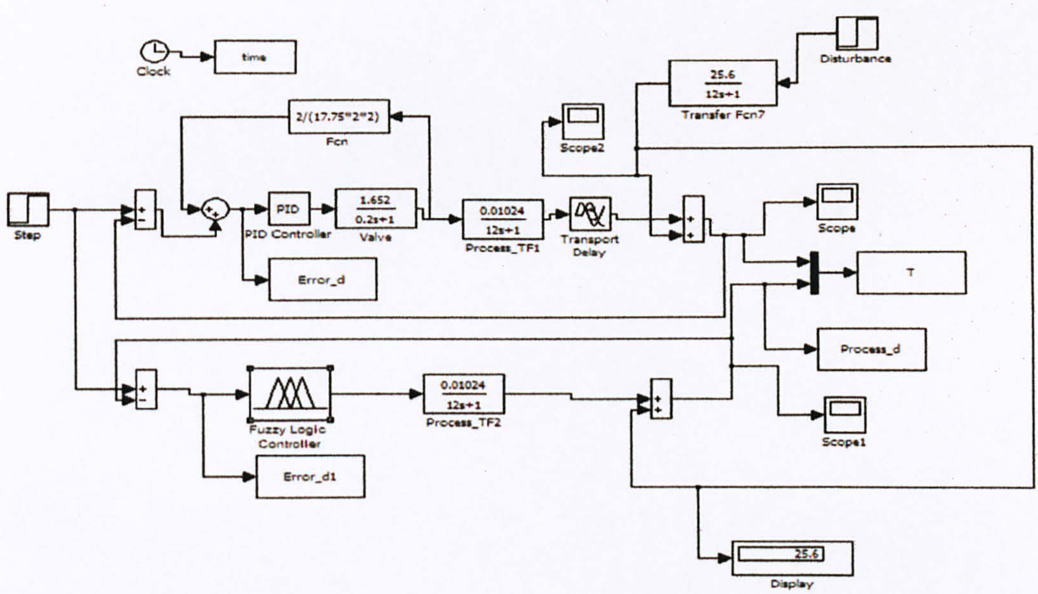


Figure 4.7: Adaptive Control Scheme block diagrams with the Fuzzy Logic Control (Disturbance change).

The FLC functions base on the Fuzzy Inference System (FIS) that consists of membership function editor, rules editor, rule viewer and surface viewer. Below figures show advanced the graphs of temperature response versus time using PID controller FLC for servomechanism problem and regulator problem:-

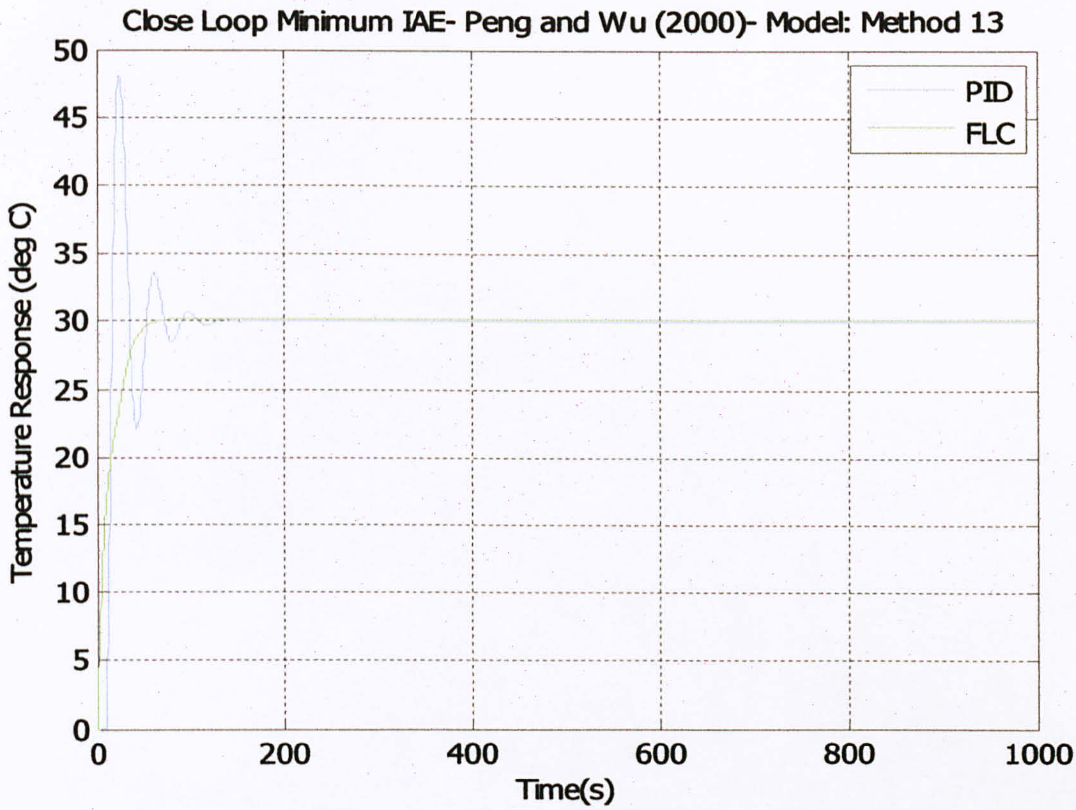


Figure 4.8: The graph of temperature response versus time for FLC and PID in Adaptive Control Scheme for set-point change. (Step input)

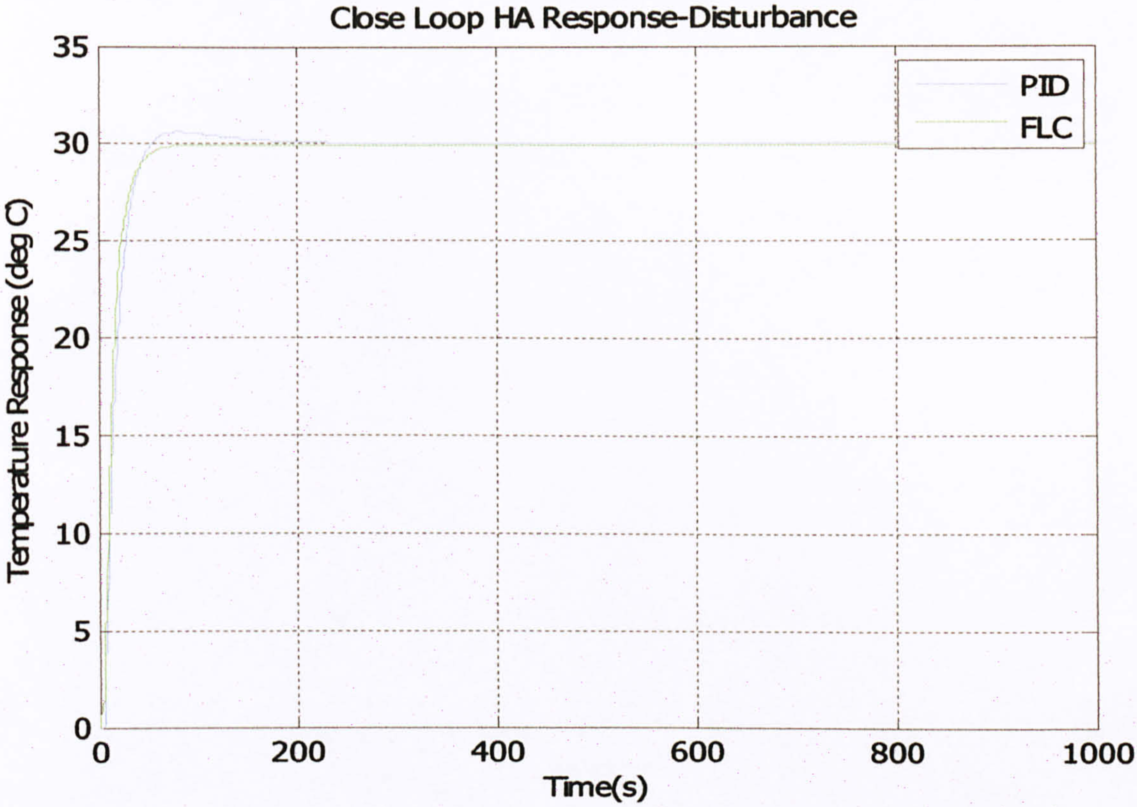


Figure 4.9: The graph of temperature response versus time for FLC and PID in Adaptive Control Scheme for disturbance change. (Disturbance input)

Both graphs above show the Temperature Response versus Time for FLC (green line) and PID Controller (blue line). From the observation, it is noticed that Fuzzy Logic Control provides a better response than the PID Controller does in both control problems. Fuzzy Logic Control is one of the advanced process control approach but differ in term of its mechanism to control the process. The conventional existing PI and PID use the tuning formula in a form of numbers and equations while Fuzzy Logic Control uses Fuzzy Logic Controller (FLC) with its own Fuzzy Set to control the process. These are the comparison table for FLC and Adaptive control:

Characteristic	Control scheme	
	Adaptive Control (PID Controller)	**Fuzzy Logic Control**
Settling Time	Approximately 130 seconds for set-point changes, and 230 seconds for disturbance changes.	Approximately 60 seconds for set-point changes and 70 seconds for disturbance changes
Oscillation	Significant oscillation for both the set-point changes and the disturbance changes.	No oscillation for both responses for the set-point and disturbance changes
Overshoot	Significant and higher overshoot for both problem the set-point change and disturbance change.	No overshoot for both responses for the set-point and disturbance changes

Table 4.3: The comparison of response between PID Controller in Adaptive Control Scheme with Fuzzy Logic Control scheme for step inputs. (Refer to **Figure 4.8** and **Figure 4.9**)

4.2 DISCUSSION

4.2.1 Controller Tuning Formula

Each controller in each advanced process control strategy has specific tuning formula that best fit with the controller and provide desired temperature response versus time. The tuning formula will affect the settling time, number of oscillations, overshoot and the area under the graph which are the main considerations that are used in analyzing the results. The controller either PI or PID need to be tuned correctly with suitable tuning formula in order to get best result. The failure in tuning the formula will give significant impact on the process control performance of the control scheme such as sluggish response, high number of oscillations and high overshoot value. In addition, the incompatibility between the tuning formula and the control scheme will cause the system become unstable.

4.2.2 Selection of the Best Control scheme

It is important to choose the graph response that has less overshoot, less oscillations, less settling time and less error. Temperature is a controlled variable that is difficult to be controlled and it takes longer time to the system to achieve new set point after set point change has taken place or to be brought back to the desired operating point once the system is disturbed. The final control variable is the temperature of water in the tank and the manipulated variable is the heat supplied by the heater. The relationship between the heat input and the temperature is given with the transfer function:

$$G(s) = \frac{0.01024}{12s+1}$$

For servomechanism problem, there is a change in temperature from initial condition of water in the tank, $25\,^{\circ}C$ to the new set point of temperature which is 30 °C. The heater is used to supply enough heat to the system to achieve the new set point. Under regulator problem, the temperature must be brought back to its initial operating point where in this project it is set to be 30 °C. The disturbance will disturb the system by increasing or decreasing the temperature and the control scheme will manipulate the heat input in order to take the system back to its set point which is 30 °C.

The selection is based on the four main considerations that have been stated earlier which are settling time, number of oscillations, overshoot and the area under the graph (Refer to **Table 4.2**). The adaptive control has been chosen as the best advanced process control scheme and as the basis of comparisons for the responses produced by Fuzzy Logic Controller scheme. In this project, it's discovered that PID controller can gives the overall best performance for step inputs for both servomechanism (set-point changes) and regulatory problem (disturbance changes). The best tuning formulas used for servomechanism problem is Minimum IAE- Peng and Wu (2000) and tuning for the regulatory problem is HA.

4.2.3 Adaptive Control (PID) versus Fuzzy Logic Control (FLC)

Fuzzy Logic Control is considered as one of the advanced process control scheme as well as an alternative to control the operating temperature of a thermal process. From the comparison which is made between the Adaptive Control and FLC, it is noticed that the FLC give better temperature response than Adaptive Control does in servomechanism and regulator control problems. The settling time is shorter; the response is quicker and the overshooting is less for FLC in both control problems. The controller in FLC controls the process base on the fuzzy setting and rules that connect the input and the output of FLC. FLC is designed base on the expertise of a human operator and it is understandable by human expert. The most important thing in designing the FLC is the ability to formulate the rules to give best performance. The advantage of FLC is the author has a better control on the controller as he could adjust and set the controller according to the current desired value. This due to it's characteristic where it will respond base on the range value of input and output membership functions and the rules that connect the input and output membership functions. It means that, it is possible and much easier to fasten or make the response slow using FLC compared to PID controller in Adaptive control.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

For this project, the main issues to be discussed are the response of the temperature in water bath system with respect to time and the application of several process control scheme. The best configuration between the type of controller, controller tuning formula and the type of advanced process control scheme will result towards the desired response of temperature in water tank. In shows that, those components are inter-related and must be considered while modeling an advanced regulatory control of a thermal process.

Base on the result run simulation and result analysis, it is concluded that Adaptive Control is the best control scheme that give the shortest time for temperature response with less number of oscillations and less value of overshooting. This control scheme also gives closest to zero value for the area under the graph.

Fuzzy Logic Control is the latest advanced control scheme. From this project, it is concluded that Adaptive Control scheme and other advanced control schemes are robust and useful in the process control. However, there are certain areas in process control in which the existing advanced process control schemes give less effective control response. The Fuzzy Logic Control is one of the alternatives that can be employed to overcome this as it has the ability to cover wider range of processes because it uses human-like techniques to define the process. Based on this project, the Fuzzy Logic Control should be considered as a new solution approach in the process control field and it also can be applied in the larger scale in the industry

5.2 RECOMMENDATION

After completing this Final Year Research Project, the author would like to make a note of a few recommendations for improvement in the future. First, the project title must be more specific to make it easier to the student to do a research on the information by stating the type of a thermal process. It will be easier to the student to understand on the project title. The expected result and the requirement to complete the project must be stated in order to assist the student in planning his schedule and defining the project scope and objective.

Another suggestion is that the current FLC designed for step input change should be further optimized to work with other kinds of inputs for example like sine wave input. But this process might become tedious and time consuming as the development and optimizing process of the FLC design itself involves lots of trial and error.

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v. B. Wayne Bequette, , (2003), **Process Control: Modeling, Design and Simulation**, Upper Saddle River, NJ, Prentice Hall.

vi. M. ABD EL-GELIEL. **"ADAPTIVE FUZZY CONTROLLER IMPLEMENTED ON THERMAL PROCESS"**. Automation Laboratory, Mannheim University (pp.1-6)

vii. Tatyana D. K. GUGULOVSKA, Lyupco N. ANTOVSKI, Mile J. STANKOVSKI and Georgi M. DIMIROVSKI (2003). **"Fuzzy Control Systems For Thermal Processes**: Synthesis, Design and Implementation". JOURNAL OF ELECTRICAL & ELECTRONICS ENGINEERING (pp. 759-773)

viii. <25 April 2009> http://www.aptronix.com/fide/whyfuzzy.htm

ix. *Fuzzy Logic Toolbox: User Guide v2*, Mathworks

APPENDICES

The block diagrams for advanced control strategies used in this project are as the following:

i. Feedback control scheme block diagram:

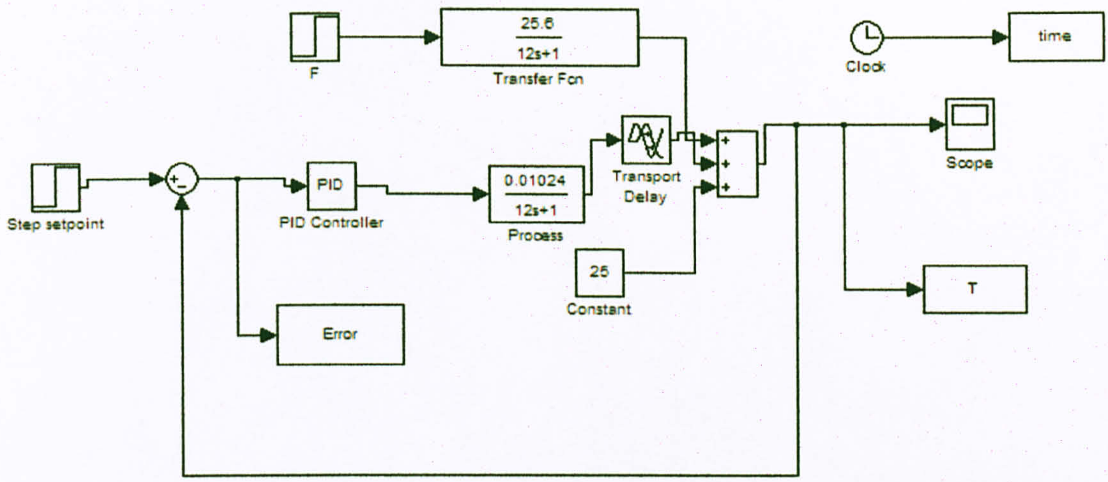


Figure A1: Feedback control scheme block diagram

ii. Feed forward

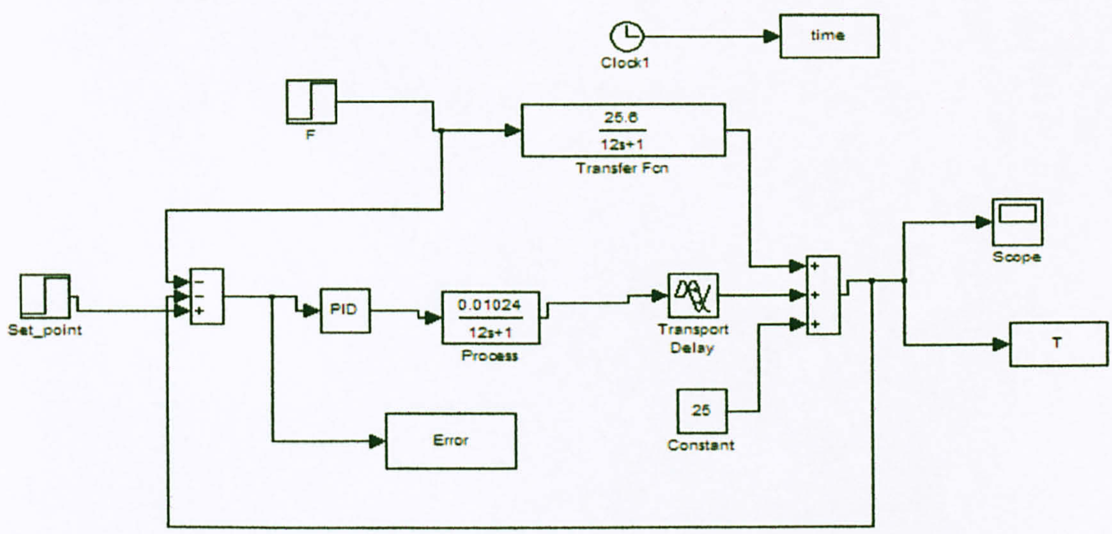


Figure A2: Feed forward control scheme block diagram

iii. Cascade

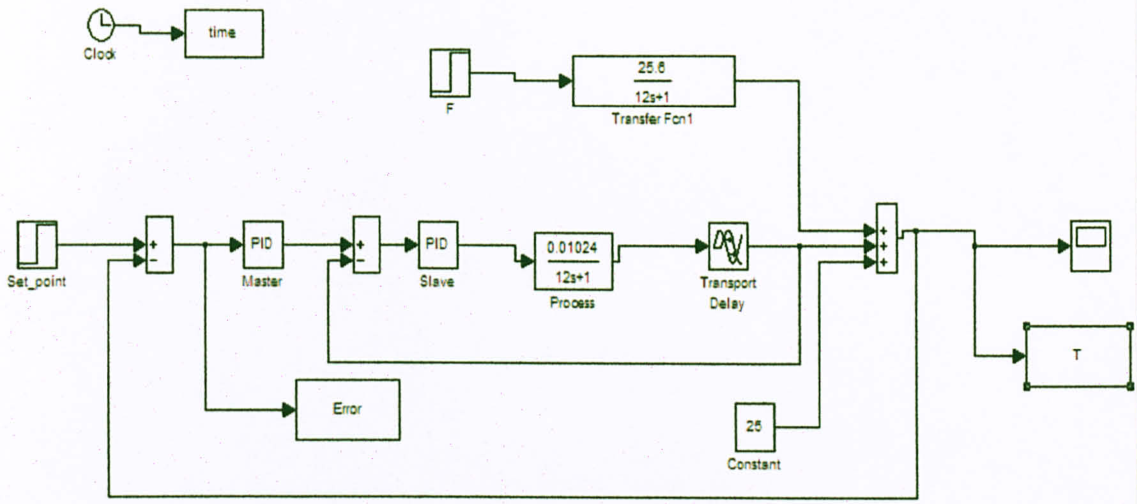


Figure A3: Cascade control scheme block diagram

RESULT: FEEDBACK CONTROL STRATEGY.

PI Controller Tuning

Set Point Change		Disturbance Change	
Tuning Formula	**Settling Time(s)**	**Tuning Formula**	**Settling Time(s)**
1. IAE Response	67000	1. IAE Response	62000
2. ITAE Response	87000	2. ITAE Response	95000
3. IMC Response	6500	3. IMC Response	7300
4. HA Response	627	4. HA Response	710

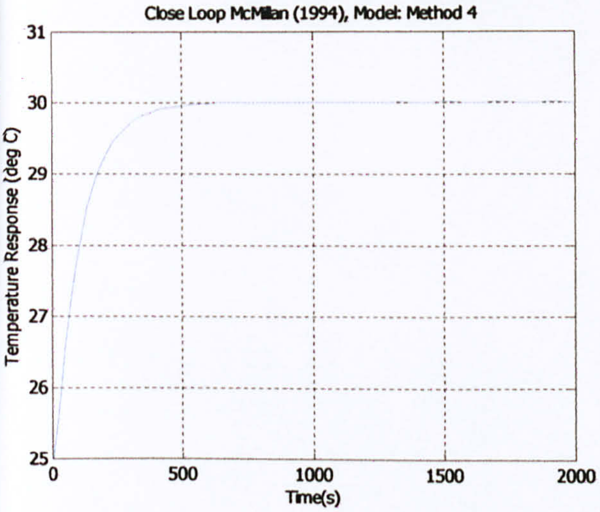
5. ISE Response	19000	5. ISE Response	18500
6. Cohen Coon Response	<5000000	6. Cohen Coon Response	<1000000
7. Ziegler and Nichols (1942) , Model Method 2	110000	7. Ziegler and Nichols (1942),Model Method 2	110000
8. Hazebroek and Van der Waerden(1950),Model Method 2	400000	8. Hazebroek and Van der Waerden(1950),Model Method 2	350000
9. Chien(1952), Servo, Model: Method 2, 0% overshoot	120000	9. Chien(1952), Servo, Model: Method 2, 0% overshoot	110000
10. Chien(1952), Servo, Model: Method 2, 20% overshoot	60000	10. Chien(1952), Servo, Model: Method 2, 20% overshoot	55000
11. Cohen and Coon (1953), Model: Method 2	400000	11. Cohen and Coon (1953), Model: Method 2	37000
12. Two Constraints Method- Wolfe (1951), Model: Method 3	25000	12. Two Constraints Method- Wolfe (1951), Model: Method 3	24000
13. Two Constraints Criterion- Murrill (1967), Model: Method 4	32000	13. Two Constraints Criterion- Murrill (1967), Model: Method 4	31000
14. McMillan (1994), Model: Method 4	540	14. McMillan (1994), Model: Method 4	675
15. St. Clair (1997), Model: Method 4	100000	15. St. Clair (1997), Model: Method 4	100000
16. Shinskey (2000), (2001) Model: Method 2	200000	16. Shinskey (2000), (2001) Model: Method 2	195000
17. Hay (1998) Servo Tuning 1, Model: Method 2	60000	17. Hay (1998) Servo Tuning 1, Model: Method 2	55000
18. Hay (1998) Servo Tuning 2, Model: Method 2	80000	18. Hay (1998) Servo Tuning 2, Model: Method 2	85000
19. Minimum IAE- Rovira et al. (1969), Model: Method 4	60000	19. Minimum IAE- Murrill (1967), Model: Method 4	49500
20. Minimum IAE- Marlin (1995), Model: Method 1	17000	20. Minimum IAE- Pemberton (1972), Smith and Corripio (1997) Model: Method 1	35000
21. Minimum IAE- Smith and Corripio (1997), Model: Method 1	52000	21. Minimum IAE- Shinskey (1988), Model: Method 1	85000
22. Minimum IAE- Hwang (1995), Model: Method	Not stable- decrease to	22. Minimum IAE- Shinskey	100000

26	negative	(1996), Model: Method 1	
23. Minimum ISE- Zhuang and Atherton (1993), Model: Method 1	Noisy response	23. Minimum IAE- Marlin (1995), Model: Method 1	5400
24. Minimum ISE- Khan and Lehman (1996), Model: Method 1	60000	24. Minimum IAE- Edgar et al.(1997), Time Delay Dominant, Model: Method 1	42000
25. Minimum ITAE- Rovira et al. (1969), Model: Method 4	70000	25. Minimum IAE- Edgar et al. (1997), Time Constant Dominant, Model: Method 1	120000
26. Minimum ISTSE- Zhuang and Atherton (1993), Model: Method 1	60000	26. Minimum IAE- Edgar et al. (1997), Model: Method 2	150000
27. Minimum ISTES- Zhuang and Atherton (1993), Model: Method 1	70000	27. Minimum IAE- Huang et al. (1996), Model: Method 1	Not Stable
		28. Minimum ISE- Hazebroek and Van der Waerden (1950), Model: Method 2	50000

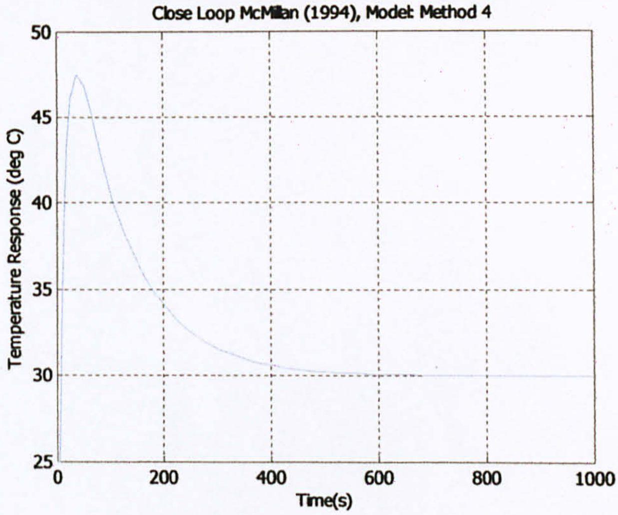
Table A1: Settling time for each PI tuning methods (Feedback)

<u>Best response</u>

i) Set point Change



ii) Disturbance change



PID Controller Tuning

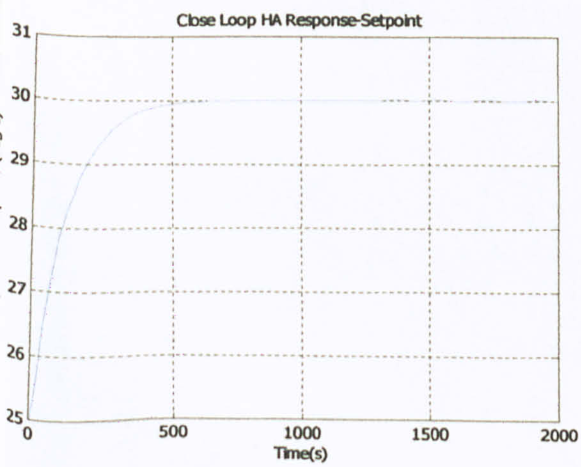
Set Point Change		Disturbance Change	
Tuning Formula	**Settling Time(s)**	**Tuning Formula**	**Settling Time(s)**
1. IAE Response	56000	1. IAE Response	62000
2. ITAE Response	90000	2. ITAE Response	90000
3. IMC Response	6800	3. IMC Response	6500
4. HA Response	620	4. HA Response	600
5. ISE Response	17000	5. ISE Response	18000
6. Cohen Coon Response	95000	6. Cohen Coon Response	<60000000
7. Parr (1989)	51000	7. Parr (1989)	58000
8. wt al. (1952)	51000	8. Three Cnstaints Method- Murrill (1967)- Method: Model 4	675
9. Chien wt al. (1952)	44000	9. Cohen and Coon (1953)- Method: Model 2	35000
10. Three Constraints Method- Murrill (1967)	710	10. Sain and Ozgen (1992)- Method: Model 15	120000
11. Three Constraints Method- Murrill (1967)	710	11. Hay (1998)- Regulator Tuning, Model: Method not specified_1	6450
12. Cohen and Coon (1953)	365000	12. Hay (1998)- Regulator Tuning, Model: Method not specified_2	7000
13. Sain and Ozgen (1992)	110000	13. Minimum IAE- Murrill (1967), Model: Method 4	25000
14. Hay (1998)- Servo Tuning, Model: Method not specified_1	42000	14. Minimum IAE- Peng and Wu (2000), Model: Method 13	Noisy response
15. Hay (1998)- Servo Tuning, Model: Method not specified_2	62000	15. Minimum IAE- Marlin (1995), Model: Method 6	18000
16. Minimum IAE- Murrill (1967)- Model: Method 4	22000	16. Modified Minimum IAE- Cheng and Hung (1985), Model: Method 8	11500
17. Minimum IAE- Peng and Wu (2000)- Model: Method 13	Noisy response	17. Minimum ISE- Murrill (1967), Model: Method	18000
18. Minimum IAE- Marlin (1995)- Model: Method 6	17000	18. Minimum ISE- Zhuang and Atherton (1993), Model: Method 1	18000
19. Modified Minimum IAE- Cheng and Hung (1985)- Model: Method 8	12000	19. Minimum ITAE- Murrill (1967), Model: Method 4	26000
20. Minimum ISE- Murrill	16500	20. Minimum ISTSE- Zhuang	21000

(1967)- Model: Method 4		and Atherton (1993), Model: Method 1	
21. Minimum ISE- Zhuang and Atherton (1993)- Model: Method 1	16500	21. Minimum ISTES- Zhuang and Atherton (1993), Model: Method 1	19500
22. Minimum ITAE- Murrill (1967)- Model: Method 4	24000	22. Minimum Error- Step load change- Gerry (1998), Model: Method 1	57000
23. Minimum ISTSE- Zhuang and Atherton (1993)- Model: Method 1	20000		
24. Minimum ISTES- Zhuang and Atherton (1993)- Model: Method 1	20000		
25. Minimum IAE- Marlin (1995)- Model: Method 1	22000		
26. Minimum IAE- Marlin (1995)- Model: Method 1	45000		
27. Minimum ISE- Wang et al. (1995)- Model: Method 1	37000		
28. Minimum ISE- Zhuang and Atherton (1993)- Model: Method 1	33500		
29. Minimum ITAE- Rovira et al. (1969)- Model: Method 4	48500		
30. Minimum ITAE- Cheng and Hung (1985)- Model: Method 8	39000		
31. Minimum ITAE- Wang et al. (1995)- Model: Method 1	50000		
32. Minimum ISTSE- Zhuang and Atherton (1993)- Model: Method 1	38000		
33. Minimum ISTES- Zhuang and Atherton (1993)- Model: Method 1	420000		

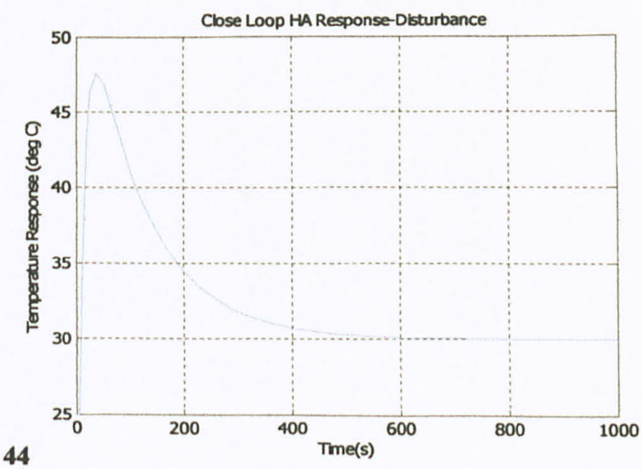
Table A2: Settling time for each PID tuning methods (Feedback)

Best response

i) Set point change



ii) Disturbance change



RESULT: FEED FORWARD CONTROL STRATEGY.

PI Controller Tuning

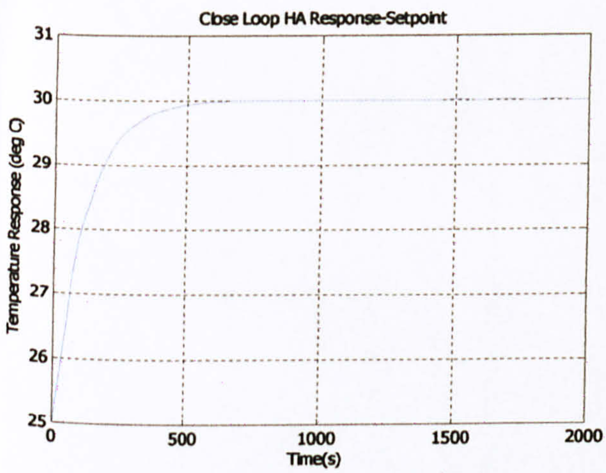
Set Point Change		Disturbance Change	
Tuning Formula	**Settling Time(s)**	**Tuning Formula**	**Settling Time(s)**
1. IAE Response	56000	1. IAE Response	60000
2. ITAE Response	86000	2. ITAE Response	90000
3. IMC Response	6000	3. IMC Response	6500
4. HA Response	622	4. HA Response	620
5. ISE Response	16500	5. ISE Response	18000
6. Cohen Coon Response	9450000	6. Cohen Coon Response	10000000
7. Ziegler and Nichols (1942) , Model Method 2	95000	7. Ziegler and Nichols (1942),Model Method 2	110000
8. Hazebroek and Van der Waerden(1950),Model Method 2	310000	8. Hazebroek and Van der Waerden(1950),Model Method 2	350000
9. Chien(1952), Servo, Model: Method 2, 0% overshoot	100000	9. Chien(1952), Servo, Model: Method 2, 0% overshoot	110000
10. Chien(1952), Servo, Model: Method 2, 20% overshoot	52000	10. Chien(1952), Servo, Model: Method 2, 20% overshoot	58000
11. Cohen and Coon (1953), Model: Method 2	33500	11. Cohen and Coon (1953), Model: Method 2	40000
12. Two Constraints Method-Wolfe (1951), Model: Method 3	22000	12. Two Constraints Method-Wolfe (1951), Model: Method 3	24000
13. Two Constraints Criterion-Murrill (1967), Model: Method 4	28000	13. Two Constraints Criterion-Murrill (1967), Model: Method 4	30000
14. McMillan (1994), Model: Method 4	28000	14. McMillan (1994), Model: Method 4	700
15. St. Clair (1997), Model: Method 4	92000	15. St. Clair (1997), Model: Method 4	100000
16. Shinskey (2000), (2001) Model: Method 2	180000	16. Shinskey (2000), (2001) Model: Method 2	200000
17. Hay (1998) Servo Tuning 1, Model: Method 2	50000	17. Hay (1998) Servo Tuning 1, Model: Method 2	55000
18. Hay (1998) Servo Tuning 2, Model: Method 2	75000	18. Hay (1998) Servo Tuning 2, Model: Method 2	86000
19. Minimum IAE- Rovira et al. (1969), Model: Method 4	60000	19. Minimum IAE- Murrill (1967), Model: Method 4	50000
20. Minimum IAE- Marlin (1995), Model: Method 1	16000	20. Minimum IAE- Pemberton (1972), Smith and Corripio (1997) Model: Method 1	34000

21. Minimum IAE- Smith and Corripio (1997), Model: Method 1	50000	21. Minimum IAE- Shinskey (1988), Model: Method 1	86000
22. Minimum IAE- Hwang (1995), Model: Method 26	Not Stable	22. Minimum IAE- Shinskey (1996), Model: Method 1	100000
23. Minimum ISE- Zhuang and Atherton (1993), Model: Method 1	Noisy response	23. Minimum IAE- Marlin (1995), Model: Method 1	5500
24. Minimum ISE- Khan and Lehman (1996), Model: Method 1	67500	24. Minimum IAE- Edgar et al.(1997), Time Delay Dominant, Model: Method 1	50000
25. Minimum ITAE- Rovira et al. (1969), Model: Method 4	67500	25. Minimum IAE- Edgar et al. (1997), Time Constant Dominant, Model: Method 1	120000
26. Minimum ISTSE- Zhuang and Atherton (1993), Model: Method 1	67500	26. Minimum IAE- Edgar et al. (1997), Model: Method 2	150000
27. Minimum ISTES- Zhuang and Atherton (1993), Model: Method 1	63000	27. Minimum IAE- Huang et al. (1996), Model: Method 1	Not stable
		28. Minimum ISE- Hazebroek and Van der Waerden (1950), Model: Method 2	50000

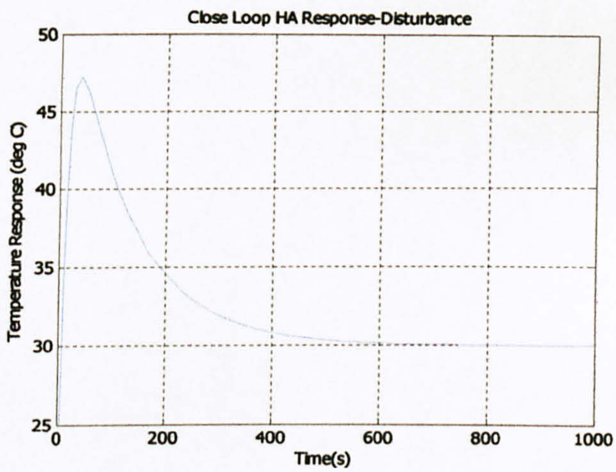
Table A3: Settling time for each PI tuning methods (Feed forward)

Best response

i) Set point Change



ii) Disturbance Change



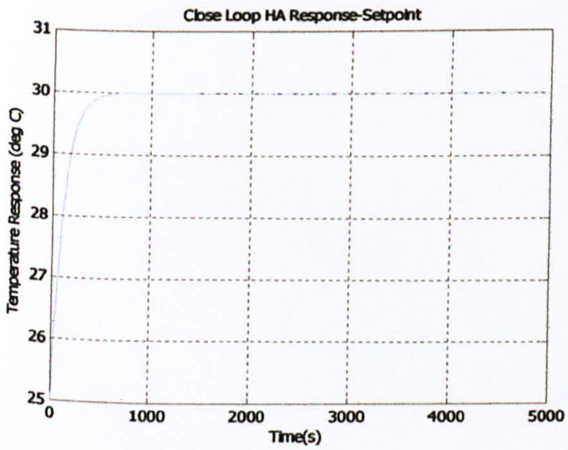
Set Point Change		Disturbance Change	
Tuning Formula	**Settling Time(s)**	**Tuning Formula**	**Settling Time(s)**
1. IAE Response	550000	1. IAE Response	60000
2. ITAE Response	820000	2. ITAE Response	100000
3. IMC Response	6000	3. IMC Response	63000
4. HA Response	600	4. HA Response	628
5. ISE Response	10000000	5. ISE Response	18000
6. Cohen Coon Response	10000000	6. Cohen Coon Response	<9000000
7. Parr (1989)	51000	7. Parr (1989)	56000
8. wt al. (1952)	50000	8. Three Cnstaints Method- Murrill (1967)- Method: Model 4	700
9. Chien wt al. (1952)	50000	9. Cohen and Coon (1953)- Method: Model 2	700
10. Three Constraints Method- Murrill (1967)	657	10. Sain and Ozgen (1992)- Method: Model 15	700
11. Three Constraints Method- Murrill (1967)	657	11. Hay (1998)- Regulator Tuning, Model: Method not specified_1	6500
12. Cohen and Coon (1953)	32000	12. Hay (1998)- Regulator Tuning, Model: Method not specified_2	7000
13. Sain and Ozgen (1992)	110000	13. Minimum IAE- Murrill (1967), Model: Method 4	24000
14. Hay (1998)- Servo Tuning, Model: Method not specified_1	42500	14. Minimum IAE- Peng and Wu (2000), Model: Method 13	Noisy response
15. Hay (1998)- Servo Tuning, Model: Method not specified_2	60000	15. Minimum IAE- Marlin (1995), Model: Method 6	18000
16. Minimum IAE- Murrill (1967)- Model: Method 4	22500	16. Modified Minimum IAE- Cheng and Hung (1985), Model: Method 8	11000
17. Minimum IAE- Peng and Wu (2000)- Model: Method 13	Noisy response	17. Minimum ISE- Murrill (1967), Model: Method	18000
18. Minimum IAE- Marlin (1995)- Model: Method 6	17000	18. Minimum ISE- Zhuang and Atherton (1993), Model: Method 1	18000
19. Modified Minimum IAE- Cheng and Hung (1985)- Model: Method 8	11000	19. Minimum ITAE- Murrill (1967), Model: Method 4	26000
20. Minimum ISE- Murrill	165000	20. Minimum ISTSE- Zhuang	22000

(1967)- Model: Method 4		and Atherton (1993), Model: Method 1	
21. Minimum ISE- Zhuang and Atherton (1993)- Model: Method 1	165000	21. Minimum ISTES- Zhuang and Atherton (1993), Model: Method 1	20000
22. Minimum ITAE- Murrill (1967)- Model: Method 4	24000	22. Minimum Error- Step load change- Gerry (1998), Model: Method 1	56000
23. Minimum ISTSE- Zhuang and Atherton (1993)- Model: Method 1	20000		
24. Minimum ISTES- Zhuang and Atherton (1993)- Model: Method 1	20000		
25. Minimum IAE- Marlin (1995)- Model: Method 1	22000		
26. Minimum IAE- Marlin (1995)- Model: Method 1	45000		
27. Minimum ISE- Wang et al. (1995)- Model: Method 1	38000		
28. Minimum ISE- Zhuang and Atherton (1993)- Model: Method 1	34000		
29. Minimum ITAE- Rovira et al. (1969)- Model: Method 4	48000		
30. Minimum ITAE- Cheng and Hung (1985)- Model: Method 8	40000		
31. Minimum ITAE- Wang et al. (1995)- Model: Method 1	50000		
32. Minimum ISTSE- Zhuang and Atherton (1993)- Model: Method 1	40000		
33. Minimum ISTES- Zhuang and Atherton (1993)- Model: Method 1	42000		

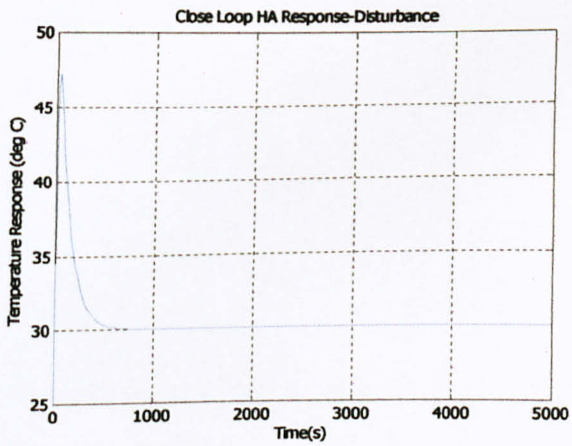
Table A3: Settling time for each PID tuning methods (Feed forward)

Best Response

i) Set point change



ii) Disturbance change



RESULT: CASCADE CONTROL STRATEGY.

PI Controller Tuning

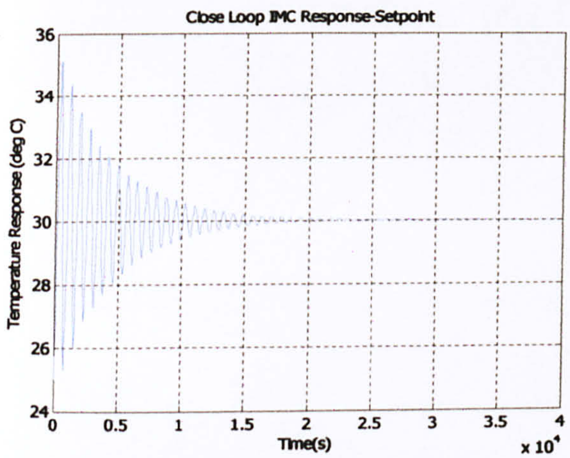
Set Point Change		Disturbance Change	
Tuning Formula	**Settling Time(s)**	**Tuning Formula**	**Settling Time(s)**
1. IAE Response	140000	1. IAE Response	110000
2. ITAE Response	200000	2. ITAE Response	170000
3. IMC Response	25000	3. IMC Response	23000
4. HA Response	Not Stable	4. HA Response	Not Stable
5. ISE Response	50000	5. ISE Response	44000
6. Cohen Coon Response	<5000000	6. Cohen Coon Response	<5000000
7. Ziegler and Nichols (1942), Model Method 2	200000	7. Ziegler and Nichols (1942),Model Method 2	200000
8. Hazebroek and Van der Waerden(1950),Model Method 2	700000	8. Hazebroek and Van der Waerden(1950),Model Method 2	540000
9. Chien(1952), Servo, Model: Method 2, 0% overshoot	250000	9. Chien(1952), Servo, Model: Method 2, 0% overshoot	210000
10. Chien(1952), Servo, Model: Method 2, 20% overshoot	145000	10. Chien(1952), Servo, Model: Method 2, 20% overshoot	120000
11. Cohen and Coon (1953), Model: Method 2	75000	11. Cohen and Coon (1953), Model: Method 2	70000
12. Two Constraints Method-Wolfe (1951), Model: Method 3	30000	12. Two Constraints Method-Wolfe (1951), Model: Method 3	30000
13. Two Constraints Criterion-Murrill (1967), Model: Method 4	70000	13. Two Constraints Criterion-Murrill (1967), Model: Method 4	65000
14. McMillan (1994), Model: Method 4	Not Stable	14. McMillan (1994), Model: Method 4	Not Stable
15. St. Clair (1997), Model: Method 4	220000	15. St. Clair (1997), Model: Method 4	180000
16. Shinskey (2000), (2001) Model: Method 2	320000	16. Shinskey (2000), (2001) Model: Method 2	320000
17. Hay (1998) Servo Tuning 1, Model: Method 2	60000	17. Hay (1998) Servo Tuning 1, Model: Method 2	55000
18. Hay (1998) Servo Tuning 2, Model: Method 2	110000	18. Hay (1998) Servo Tuning 2, Model: Method 2	100000
19. Minimum IAE- Rovira et al. (1969), Model: Method 4	120000	19. Minimum IAE- Murrill (1967), Model: Method 4	100000
20. Minimum IAE- Marlin (1995), Model: Method 1	50000	20. Minimum IAE- Pemberton (1972), Smith and Corripio (1997) Model: Method 1	70000

21. Minimum IAE- Smith and Corripio (1997), Model: Method 1	120000	21. Minimum IAE- Shinskey (1988), Model: Method 1	150000
22. Minimum IAE- Hwang (1995), Model: Method 26	Not Stable	22. Minimum IAE- Shinskey (1996), Model: Method 1	170000
23. Minimum ISE- Zhuang and Atherton (1993), Model: Method 1	Not Stable	23. Minimum IAE- Marlin (1995), Model: Method 1	Not Stable
24. Minimum ISE- Khan and Lehman (1996), Model: Method 1	120000	24. Minimum IAE- Edgar et al.(1997), Time Delay Dominant, Model: Method 1	100000
25. Minimum ITAE- Rovira et al. (1969), Model: Method 4	120000	25. Minimum IAE- Edgar et al. (1997), Time Constant Dominant, Model: Method 1	200000
26. Minimum ISTSE- Zhuang and Atherton (1993), Model: Method 1	120000	26. Minimum IAE- Edgar et al. (1997), Model: Method 2	250000
27. Minimum ISTES- Zhuang and Atherton (1993), Model: Method 1	150000	27. Minimum IAE- Huang et al. (1996), Model: Method 1	Not Stable
		28. Minimum ISE- Hazebroek and Van der Waerden (1950), Model: Method 2	90000

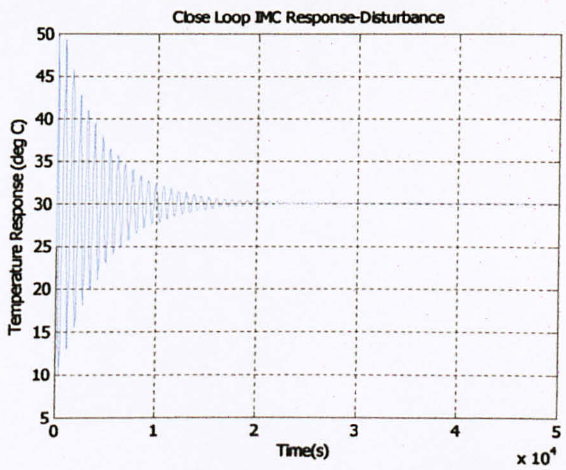
Table A4: Settling time for each PI tuning methods (Cascade)

<u>Best Response</u>

i) Set point change



ii) Disturbance change



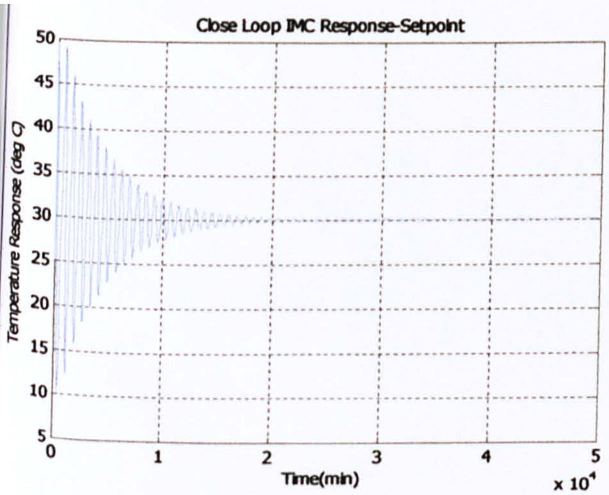
Set Point Change		Disturbance Change	
Tuning Formula	**Settling Time(s)**	**Tuning Formula**	**Settling Time(s)**
1. IAE Response	120000	1. IAE Response	110000
2. ITAE Response	170000	2. ITAE Response	165000
3. IMC Response	23000	3. IMC Response	23000
4. HA Response	Not Stable	4. HA Response	Not Stable
5. ISE Response	43000	5. ISE Response	41000
6. Cohen Coon Response	<8000000	6. Cohen Coon Response	<8000000
7. Parr (1989)	Not Stable	7. Parr (1989)	100000
8. wt al. (1952)	Not Stable	8. Three Cnstaints Method- Murrill (1967)- Method: Model 4	Not Stable
9. Chien wt al. (1952)	Not Stable	9. Cohen and Coon (1953)- Method: Model 2	65000
10. Three Constraints Method- Murrill (1967)	Not Stable	10. Sain and Ozgen (1992)- Method: Model 15	210000
11. Three Constraints Method- Murrill (1967)	Not Stable	11. Hay (1998)- Regulator Tuning, Model: Method not specified_1	12000
12. Cohen and Coon (1953)	Not Stable	12. Hay (1998)- Regulator Tuning, Model: Method not specified_2	12000
13. Sain and Ozgen (1992)	Not Stable	13. Minimum IAE- Murrill (1967), Model: Method 4	52000
14. Hay (1998)- Servo Tuning, Model: Method not specified_1	Not Stable	14. Minimum IAE- Peng and Wu (2000), Model: Method 13	Not Stable
15. Hay (1998)- Servo Tuning, Model: Method not specified_2	Not Stable	15. Minimum IAE- Marlin (1995), Model: Method 6	50000
16. Minimum IAE- Murrill (1967)- Model: Method 4	Not Stable	16. Modified Minimum IAE- Cheng and Hung (1985), Model: Method 8	27000
17. Minimum IAE- Peng and Wu (2000)- Model: Method 13	Not Stable	17. Minimum ISE- Murrill (1967), Model: Method	45000
18. Minimum IAE- Marlin (1995)- Model: Method 6	Not Stable	18. Minimum ISE- Zhuang and Atherton (1993), Model: Method 1	44000
19. Modified Minimum IAE- Cheng and Hung (1985)- Model: Method 8	Not Stable	19. Minimum ITAE- Murrill (1967), Model: Method 4	53000
20. Minimum ISE- Murrill	Not Stable	20. Minimum ISTSE- Zhuang	50000

(1967)- Model: Method 4		and Atherton (1993), Model: Method 1	
21. Minimum ISE- Zhuang and Atherton (1993)- Model: Method 1	Not Stable	21. Minimum ISTES- Zhuang and Atherton (1993), Model: Method 1	45000
22. Minimum ITAE- Murrill (1967)- Model: Method 4	Not Stable	22. Minimum Error- Step load change- Gerry (1998), Model: Method 1	120000
23. Minimum ISTSE- Zhuang and Atherton (1993)- Model: Method 1	Not Stable		
24. Minimum ISTES- Zhuang and Atherton (1993)- Model: Method 1	Not Stable		
25. Minimum IAE- Marlin (1995)- Model: Method 1	Not Stable		
26. Minimum IAE- Marlin (1995)- Model: Method 1	Not Stable		
27. Minimum ISE- Wang et al. (1995)- Model: Method 1	Not Stable		
28. Minimum ISE- Zhuang and Atherton (1993)- Model: Method 1	Not Stable		
29. Minimum ITAE- Rovira et al. (1969)- Model: Method 4	Not Stable		
30. Minimum ITAE- Cheng and Hung (1985)- Model: Method 8	Not Stable		
31. Minimum ITAE- Wang et al. (1995)- Model: Method 1	Not Stable		
32. Minimum ISTSE- Zhuang and Atherton (1993)- Model: Method 1	Not Stable		
33. Minimum ISTES- Zhuang and Atherton (1993)- Model: Method 1	Not Stable		

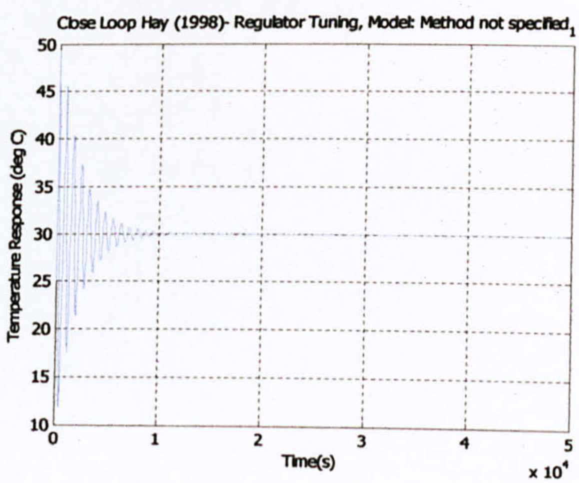
Table A5: Settling time for each PID tuning methods (Cascade)

Best response

i) Set Point



ii) Disturbance change



RESULT: ADAPTIVE CONTROL STRATEGY.

PI Controller Tuning

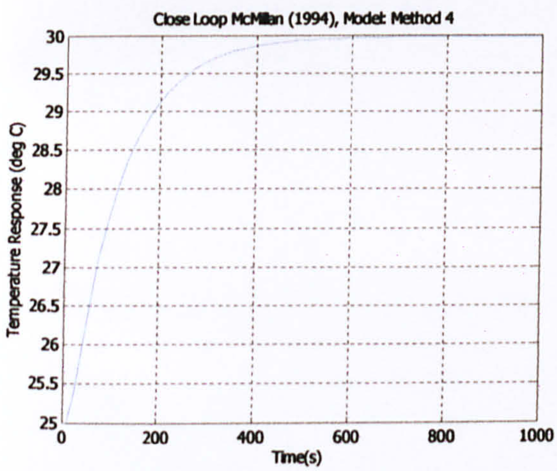
Set Point Change		Disturbance Change	
Tuning Formula	**Settling Time(s)**	**Tuning Formula**	**Settling Time(s)**
1. IAE Response	80000	1. IAE Response	54000
2. ITAE Response	100000	2. ITAE Response	80000
3. IMC Response	10000	3. IMC Response	6000
4. HA Response	727	4. HA Response	525
5. ISE Response	22000	5. ISE Response	16000
6. Cohen Coon Response	< 800000	6. Cohen Coon Response	< 800000
7. Ziegler and Nichols (1942) , Model Method 2	125000	7. Ziegler and Nichols (1942),Model Method 2	100000
8. Hazebroek and Van der Waerden(1950),Model Method 2	400000	8. Hazebroek and Van der Waerden(1950),Model Method 2	300000
9. Chien(1952), Servo, Model: Method 2, 0% overshoot	140000	9. Chien(1952), Servo, Model: Method 2, 0% overshoot	100000
10. Chien(1952), Servo, Model: Method 2, 20% overshoot	70000	10. Chien(1952), Servo, Model: Method 2, 20% overshoot	50000
11. Cohen and Coon (1953), Model: Method 2	45000	11. Cohen and Coon (1953), Model: Method 2	32500
12. Two Constraints Method-Wolfe (1951), Model: Method 3	27000	12. Two Constraints Method-Wolfe (1951), Model: Method 3	21000
13. Two Constraints Criterion-Murrill (1967), Model: Method 4	40000	13. Two Constraints Criterion-Murrill (1967), Model: Method 4	27500
14. McMillan (1994), Model: Method 4	683	14. McMillan (1994), Model: Method 4	512
15. St. Clair (1997), Model: Method 4	120000	15. St. Clair (1997), Model: Method 4	100000
16. Shinskey (2000), (2001) Model: Method 2	220000	16. Shinskey (2000), (2001) Model: Method 2	200000
17. Hay (1998) Servo Tuning 1, Model: Method 2	62500	17. Hay (1998) Servo Tuning 1, Model: Method 2	50000
18. Hay (1998) Servo Tuning 2, Model: Method 2	100000	18. Hay (1998) Servo Tuning 2, Model: Method 2	75000
19. Minimum IAE- Rovira et al. (1969), Model: Method 4	75000	19. Minimum IAE- Murrill (1967), Model: Method 4	50000
20. Minimum IAE- Marlin (1995), Model: Method 1	22000	20. Minimum IAE- Pemberton (1972), Smith and Corripio (1997) Model: Method 1	30000

21. Minimum IAE- Smith and Corripio (1997), Model: Method 1	68000	21. Minimum IAE- Shinskey (1988), Model: Method 1	75000
22. Minimum IAE- Hwang (1995), Model: Method 26	Not stable	22. Minimum IAE- Shinskey (1996), Model: Method 1	100000
23. Minimum ISE- Zhuang and Atherton (1993), Model: Method 1	Noisy response	23. Minimum IAE- Marlin (1995), Model: Method 1	5000
24. Minimum ISE- Khan and Lehman (1996), Model: Method 1	80000	24. Minimum IAE- Edgar et al.(1997), Time Delay Dominant, Model: Method 1	38000
25. Minimum ITAE- Rovira et al. (1969), Model: Method 4	80000	25. Minimum IAE- Edgar et al. (1997), Time Constant Dominant, Model: Method 1	110000
26. Minimum ISTSE- Zhuang and Atherton (1993), Model: Method 1	80000	26. Minimum IAE- Edgar et al. (1997), Model: Method 2	130000
27. Minimum ISTES- Zhuang and Atherton (1993), Model: Method 1	80000	27. Minimum IAE- Huang et al. (1996), Model: Method 1	Not Stable
		28. Minimum ISE- Hazebroek and Van der Waerden (1950), Model: Method 2	50000

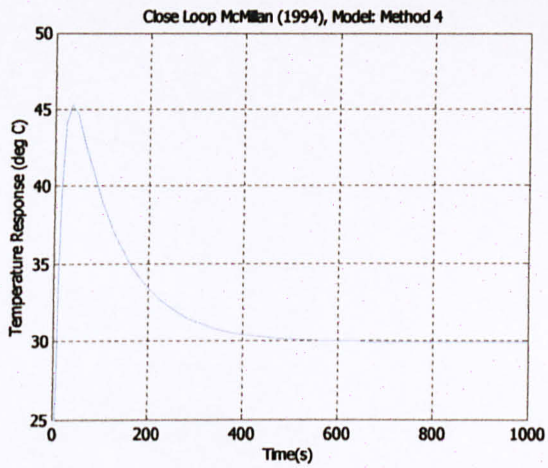
Table A6: Settling time for each PI tuning methods (Adaptive)

Best response

i) Set point



ii) Disturbance change



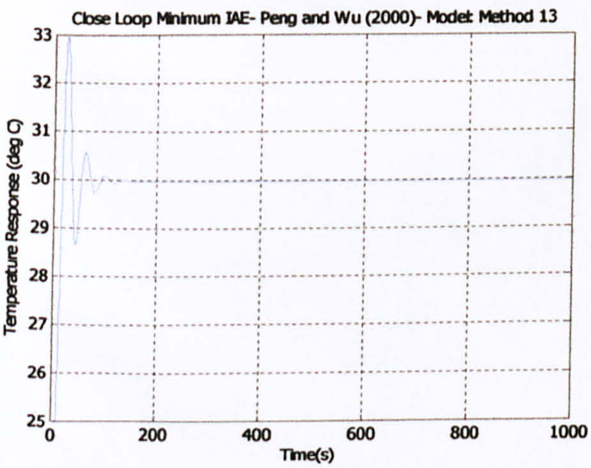
Set Point Change		Disturbance Change	
Tuning Formula	**Settling Time(s)**	**Tuning Formula**	**Settling Time(s)**
1. IAE Response	43800	1. IAE Response	33000
2. ITAE Response	64800	2. ITAE Response	49000
3. IMC Response	4760	3. IMC Response	3500
4. HA Response	400	4. HA Response	320
5. ISE Response	13000	5. ISE Response	10000
6. Cohen Coon Response	<900000	6. Cohen Coon Response	<1000000
7. Parr (1989)	41000	7. Parr (1989)	31000
8. wt al. (1952)	41000	8. Three Cnstaints Method- Murrill (1967)- Method: Model 4	400
9. Chien wt al. (1952)	34700	9. Cohen and Coon (1953)- Method: Model 2	20000
10. Three Constraints Method- Murrill (1967)	465	10. Sain and Ozgen (1992)- Method: Model 15	66000
11. Three Constraints Method- Murrill (1967)	465	11. Hay (1998)- Regulator Tuning, Model: Method not specified_1	3600
12. Cohen and Coon (1953)	25000	12. Hay (1998)- Regulator Tuning, Model: Method not specified_2	5000
13. Sain and Ozgen (1992)	87700	13. Minimum IAE- Murrill (1967), Model: Method 4	13000
14. Hay (1998)- Servo Tuning, Model: Method not specified_1	33800	14. Minimum IAE- Peng and Wu (2000), Model: Method 13	150
15. Hay (1998)- Servo Tuning, Model: Method not specified_2	47800	15. Minimum IAE- Marlin (1995), Model: Method 6	10000
16. Minimum IAE- Murrill (1967)- Model: Method 4	17200	16. Modified Minimum IAE- Cheng and Hung (1985), Model: Method 8	6000
17. Minimum IAE- Peng and Wu (2000)- Model: Method 13	130	17. Minimum ISE- Murrill (1967), Model: Method	10000
18. Minimum IAE- Marlin (1995)- Model: Method 6	13000	18. Minimum ISE- Zhuang and Atherton (1993), Model: Method 1	10000
19. Modified Minimum IAE- Cheng and Hung (1985)- Model: Method 8	8150	19. Minimum ITAE- Murrill (1967), Model: Method 4	15000
20. Minimum ISE- Murrill	13000	20. Minimum ISTSE- Zhuang	12000

(1967)- Model: Method 4		and Atherton (1993), Model: Method 1	
21. Minimum ISE- Zhuang and Atherton (1993)- Model: Method 1	13000	21. Minimum ISTES- Zhuang and Atherton (1993), Model: Method 1	11000
22. Minimum ITAE- Murrill (1967)- Model: Method 4	18800	22. Minimum Error- Step load change- Gerry (1998), Model: Method 1	30000
23. Minimum ISTSE- Zhuang and Atherton (1993)- Model: Method 1	15500		
24. Minimum ISTES- Zhuang and Atherton (1993)- Model: Method 1	14400		
25. Minimum IAE- Marlin (1995)- Model: Method 1	17350		
26. Minimum IAE- Marlin (1995)- Model: Method 1	17320		
27. Minimum ISE- Wang et al. (1995)- Model: Method 1	29350		
28. Minimum ISE- Zhuang and Atherton (1993)- Model: Method 1	26600		
29. Minimum ITAE- Rovira et al. (1969)- Model: Method 4	38400		
30. Minimum ITAE- Cheng and Hung (1985)- Model: Method 8	30850		
31. Minimum ITAE- Wang et al. (1995)- Model: Method 1	39000		
32. Minimum ISTSE- Zhuang and Atherton (1993)- Model: Method 1	30000		
33. Minimum ISTES- Zhuang and Atherton (1993)- Model: Method 1	33400		

Table A7: Settling time for each PID tuning methods (Adaptive)

<u>Best response</u>

i) Set point change



ii) Disturbance change